TM 1-400

WAR DEPARTMENT

U.S. Dept. of Army

TECHNICAL MANUAL

THEORY OF FLIGHT

February 24, 1941

TECHNICAL MANUAL

THEORY OF FLIGHT

CHANGES No. 1

WAR DEPARTMENT,
WASHINGTON, March 4, 1942.

TM 1–400, February 24, 1941, is changed as follows:

The formula (51) in paragraph 98*b* is changed to read as follows:

$$A_s = 0.605 D^2$$

[A. G. 062.11 (5–1–41).] (C 1, Mar. 4, 1942.)

BY ORDER OF THE SECRETARY OF WAR:

G. C. MARSHALL,
Chief of Staff.

OFFICIAL:

J. A. ULIO,
Major General,
The Adjutant General.

*These changes supersede section I, Training Circular No. 29, War Department, 1941.

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TECHNICAL MANUAL

THEORY OF FLIGHT

CHANGES No. 2 }

WAR DEPARTMENT,
WASHINGTON, April 2, 1943.

TM 1-400, February 21, 1941, is changed as follows:

42. Airfoil profiles.

*   *   *   *   *   *   *

c. An additional family * * * of five digits. **As in the four-digit system of designation, the first digit indicates the relative magnitude of the camber and the last two indicate the thickness of the airfoil section. The second and third digits, however, form a pair which together indicate the mean-line shape for which the position of camber is one of the parameters.** Thus N. A. C. A. 22015 airfoil has a **nominal** maximum camber of the mean line of two percent of the chord **and a maximum** thickness of 15 percent of the chord. **The actual camber, however, is listed in the table below. The second and third digits, 20, indicate that the camber is 1.5 percent of the chord at a point 0.10C from the leading edge, as shown in the following table:**

Camber designation (first digit)						
	Mean-line shape designation (second and third digits)	10	20	30	40	50
	Position of camber, percent of chord	5	10	15	20	25
		Actual camber percent of chord				
2		1.1	1.5	1.8	2.1	2.3
3			2.3	2.8	3.1	
4			3.1	3.7	4.2	
6			4.6	5.5	6.2	

*   *   *   *   *   *   *

[A. G. 062.11 (3-22-43).] (C 2, Apr. 2, 1943.)

BY ORDER OF THE SECRETARY OF WAR:

G. C. MARSHALL,
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U. S. GOVERNMENT PRINTING OFFICE: 1943

TECHNICAL MANUAL No. 1-400 } WAR DEPARTMENT, WASHINGTON, *February 24, 1941.*

THEORY OF FLIGHT

Prepared under direction of the Chief of the Air Corps

SECTION I

GENERAL

1. Purpose.—The purpose of this manual is to provide—

a. The technical training necessary to understand and obey the technical orders and instructions covering the use and operation of military aircraft.

b. A working knowledge of the mechanical and physical laws which govern airplane performance, creates a proper respect for the limitations of the airplane, and a corresponding increase in the efficiency of operations.

c. A working knowledge of the progress of aeronautical research sufficient that in conversation an Air Corps officer's remarks may reflect credit upon himself and the military service.

2. Mathematics.—*a.* The student will be required to understand problems involving the squares and square roots of numbers, but equations involving powers higher than the second and fractional powers

*This manual supersedes TR 1170-205, March 1, 1937.

have been reduced to a minimum. Likewise, calculus is excluded from the discussion, and trigonometry is mentioned only at the rare intervals when avoiding it would appear to lead to complications.

b. That the airplane flies is a physical reality, but what makes it fly involves a knowledge of fundamental physical conceptions. Students whose previous educational experience has not fitted them to cope with physical conceptions, such as force, mass, length, motion, and dimension, must acquire a working knowledge of them before an understanding of what makes an airplane fly can be acquired.

3. **History.**—*a.* At approximately half past ten o'clock on the morning of December 17, 1903, Orville Wright piloted the famous Wright powered biplane a distance of a little over 120 feet in 12 seconds, at a maximum altitude of 10 feet and at a speed of slightly over 31 miles per hour. That flight, which has gone down in history as man's first successful attempt to stay aloft in a heavier-than-air craft, was one of the four flights made that historic morning at Kitty Hawk, N. C., the longest of which was made by the late Wilbur Wright for a distance of 852 feet in 59 seconds. During the 5 years following the first flight no fundamental changes were made in the original airplane, which controlled lateral stability by warping the after portion of the wing tip section in such a way as to vary the camber at the tips.

b. Until the outbreak of the World War, aircraft design and construction had very little scientific or engineering data as a basis. Stresses in flight were largely unknown and the aerodynamics of balance and control were vaguely understood. The theory of stability was quite unappreciated and wing sections in use were inefficient. Great strides, however, were made in experimentation. Important patents were taken out. The industrial field was scoured for suitable materials, and familiar structural principles were gradually applied to this new field. In this early period the records of failure and of achievement in aeronautical activity served as the backbone of the science rather than the supporting theory, which later was quickly built up as a result of wind tunnel investigations, flight tests, and application of physical laws.

c. The academic interest evinced by scientists in aeronautical problems was supplemented by energetic application shortly after the outbreak of the World War. The employment of airplanes as a valuable asset in warfare made accessible resources that private interests, stimulated by pioneering enthusiasm or ultimate financial profit, could never have effected. Engineers and scientists at home and abroad in a veritable orgy of investigation set about making aircraft a new weapon.

4. Airplane.—The airplane in order to be considered as a useful vehicle must perform a certain duty. The duty of an airplane is the expeditious transportation of the "pay" load, the military, passenger, or cargo parts of the so-called "useful" load.

a. Requirements.—(1) In general, problems involving air and water craft are fairly similar. Both must have the following essential requirements:

(*a*) A medium of support for the craft which in the case of the airplane is a dynamic reaction with the air.

(*b*) A proper housing and protection for the crew and equipment which is carried.

(*c*) A means of propulsion or driving force.

(*d*) A provision for navigation of the craft, that is, the crew must be able to steer it in the desired direction and keep it under proper control at all times.

(*e*) The airplane, in addition, must be provided with a means of taking off from or alighting on either land or water, without damage to itself or to the crew and cargo carried.

(2) A successful airplane will at best be a compromise, owing to conflicting requirements. Thus an airplane designed for ease of overhaul may offer parasite resistance greater than that occurring where this feature is neglected. Again visibility must be sacrificed for aerodynamic efficiency. On the whole then, the successful airplane must meet the requirements which are listed below in the order of their relative importance:

(*a*) The design must be such that the airplane will best perform the functions for which it is built.

(*b*) Repair and maintenance in the field must require a minimum of time and expense.

(*c*) The airplane must be built as cheaply and simply as possible.

(*d*) The airplane must be aerodynamically efficient or must have a maximum of speed and climbing ability with a minimum of power.

b. Essential parts.—The essential parts that meet the requirements in *a* above are divided into five groups:

(1) The first requirement is a means of sustentation. The wings of the airplane are the surfaces which are designed to take the forces lifting the airplane when it is moving rapidly through the air. The hull of a ship, on the other hand, is subject to the buoyant forces of the water displaced and the ship is sustained on the water. However, the wings are more comparable to the board of an aquaplane, which is sustained on the surface by dynamic rather than static forces.

(2) The second requirement, proper housing, is met by the fuselage, nacelle, or boat hull of the airplane, just as the ship's hull houses the crew and cargo.

(3) The gasoline engine and the air crew or, as the combination is generally known, the "engine-propeller" unit fulfill the third requirement, giving power to pull the airplane through the air. In the case of the aquaplane, the engine-propeller unit is the towing boat, applying the pulling force through the towline.

(4) The fourth requirement is fulfilled by the "control surfaces" which are required to enable the crew to direct the flight of the craft.

(*a*) The airplane is unique in that the pilot must be provided with devices to control it about its three principal axes. A ship operating on the surface of the water needs but one control, the rudder, for changing direction. The submarine when submerged needs two controls, the rudder for changing the direction in the horizontal plane and the elevators for changing direction in the vertical plane (rising or diving).

(*b*) The airplane needs both rudder and elevators, and, in addition, a third or lateral control, primarily for keeping the airplane on an even keel in straight flight and for maintaining a proper attitude in circling flight.

(5) The landing gear fulfills the fifth or distinctive requirement for the airplane, supporting it when at rest or when taking off or making a landing. It has no useful function once the airplane is in flight, whether it is of the wheel or float type.

c. Vital characteristics.—The designer of an airplane, having available an engine of given power to carry a specified weight, does his best to embody the following characteristics in the completed airplane:

(1) Lowest feasible landing speed for a given area of wings.
(2) Greatest possible high speed.
(3) Best rate of climb.
(4) Desirable amount of stability.
(5) Maximum visibility.
(6) Minimum structural weight for adequate strength.
(7) Minimum parasite resistance.
(8) Low cost.

The first three characteristics mentioned hinge primarily on the selection of the airfoil or airfoil combination. Stability and visibility depend largely on the arrangement of the structure or lay-out. The remaining characteristics are associated with the selection and fabrication of structural materials.

d. Structural qualities.—In addition to the characteristics vital to performance, there are certain structural qualities essential to successful operation. These are—

(1) Sufficient rigidity to prevent vibration and distortion.

(2) Enough flexibility to absorb and distribute sudden shocks and uneven strains.

(3) Fabricated parts of type such as to show definite signs of deterioration prior to absolute failure.

(4) Material of high strength-weight factor to insure lightness.

(5) Material which is homogeneous, resistant to fatigue, shock, stress reversal, etc.

(6) Maximum resistance to deterioration due to corrosion, decay, etc.

(7) Structure readily accessible for inspection and repair and also designed for ease of overhaul of power plant and equipment.

5. Nomenclature.—In order to "speak the language" of aeronautics complete familiarity with aviation terms is necessary together with the accepted definitions of these terms. The current publication of the National Advisory Committee for Aeronautics entitled "Nomenclature for Aeronautics" should be considered as part of this manual and reference to that publication should be made often.

6. Notation.—The following notation which is used in this manual is consistent with the standard adopted by the National Advisory Committee for Aeronautics and the usage of the Matériel Division, Air Corps.

A_e	=equivalent parasite area.
A_s	=effective area of the propeller slipstream.
a	=acceleration, foot per second ^{2}.
AR	=aspect ratio=b^2/S.
b	=span, feet.
B hp	=brake horsepower of engine.
c	=chord, feet.
c. g.	=center of gravity.
c. p.	=center of pressure, distance from leading edge.
C	=coefficient; degrees centigrade.
C_D	=drag coefficient.
C_{Di}	=induced drag coefficient.
C_{Do}	=profile drag coefficient.
C_{Dp}	=parasite drag coefficient.
C_L	=lift coefficient.
C_m	=moment coefficient.
C_p	=power coefficient.

D	=drag, pounds; diameter, feet.
F	=force; degrees Farenheit.
G	=gap, feet.
g	=acceleration of gravity=32.2 feet per seconds.[2]
H	=total pressure head, feet; horizontal force, pounds.
h	=potential pressure head, feet.
HP	=horsepower.
HP_a	=horsepower available.
HP_r	=horsepower required.
i	=angle; angle of incidence.
k	=a constant.
K	=a constant.
K_y	=engineering lift coefficient.
K_x	=engineering drag coefficient.
l	=length, feet.
L	=lift, pound; linear dimension.
LE	=leading edge.
m	=mass, slugs.
m.a.c.	=mean aerodynamic chord.
M	=pitching moment, moment, pound-foot.
n	=revolutions per second.
N	=revolutions per minute.
P	=power, foot-pounds per second; pressure pounds per square foot.
P_a	=power available.
P_r	=power required.
Q	=torque, pound-foot; torque force, pound.
r	=radius, feet.
R	=resultant force, pound; a constant; propeller radius, feet.
RN	=Reynolds number=$Vl\ \rho/\mu$.
S	=surface, square feet.
t	=thickness, feet; time, seconds.
T	=thrust, pound; time, seconds; absolute temperature.
TE	=trailing edge.
V	=velocity, feet per second; volume, cubic feet[3]; vertical force, pounds.
V_c	=velocity of circulation.
V_i	=inflow velocity, feet per second.
V_s	=slipstream velocity, feet per second.
V_R	=resultant velocity, feet per second.
W	=mg=weight, pounds.

Greek symbols

α (alpha) = angle of attack; angle.
α_0 = angle of attack at infinite aspect ratio.
β (beta) = angle; blade angle.
ϵ (epsilon) = angle of downwash, degrees.
Δ (Delta) = increment.
θ (theta) = angle; angle of pitch.
η (eta) = propeller efficiency.
μ (mu) = viscosity, pounds-seconds per square foot.
ν (nu) = kinematic viscosity, square feet per second.
π (pi) = 3.1416.
ρ (rho) = mass density; for standard air at sea level = 0.00238 slugs per cubic foot.
ω (omega) = angular velocity, radians-second.
Σ (Sigma) = sum.
σ (sigma) = density ratio.
ϕ (phi) = angle of roll, degrees.
ψ (psi) = angle of yaw, degrees.

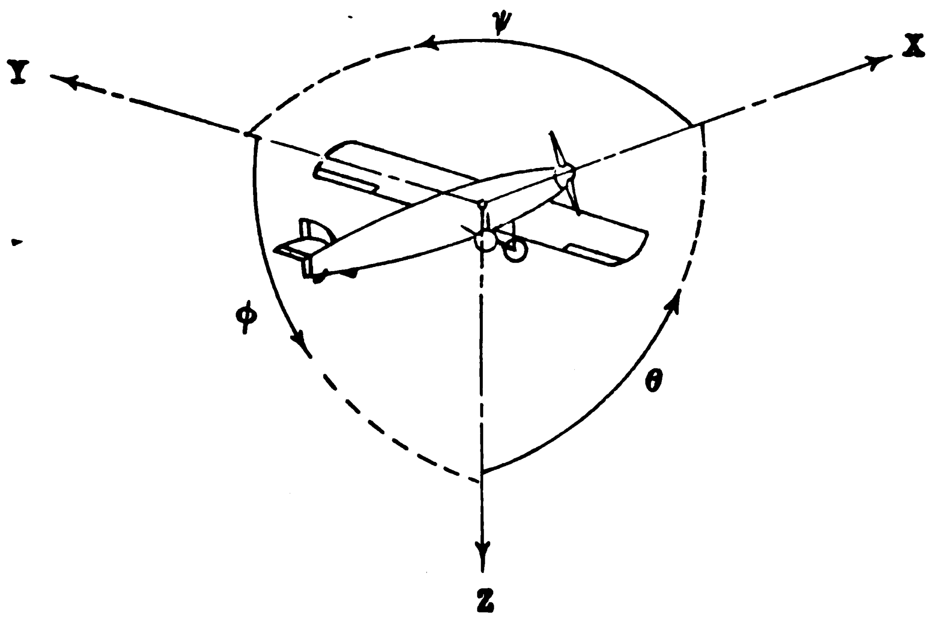


FIGURE 1.—Positive directions of axes and angles for motion of complete airplane.

Section II

FUNDAMENTALS OF AERODYNAMICS

7. Definition.—Officially defined by the National Advisory Committee for Aeronautics, aerodynamics is the branch of dynamics which treats of motion of the air and other gaseous fluids and of the forces on solids in motion relative to such fluids. This science, one of the branches of physics, offers the basic principles of flight and is the mainstay of aeronautics.

8. Purpose.—*a.* The purpose of this section is to present the salient principles of flight without recourse to higher mathematics and without exhaustive analysis. This is due to the fact that the time which is and could possibly be allotted to theory of flight precludes a complete treatment. Many excellent texts are available on aerodynamics. The student who desires to amplify his knowledge beyond the scope of this manual may refer to some of the commercially published volumes, and the reports and technical notes of the National Advisory Committee on Aeronautics.

b. To acquire the basic facts and theories of aerodynamics, initial understanding must embrace pertinent fundamental physical laws and concepts. The air must be appreciated as a fluid having mass and weight and as having motion which is, as all motion, purely relative.

c. The construction and operation of the wind tunnel are dealt with since it has proved invaluable to aerodynamics and to airplane development.

d. With these considerations as a background it is possible to proceed with the salient phases of aerodynamics, including airfoil characteristics, dimensions and combinations, parasite drag, balance, stability, propeller theory, performance, controllability, and maneuverability. No attempt is made at complete treatment. Rather are those principles stressed which account for the airplane in its present form and for its behavior in flight. These are the items of primary interest to operating personnel.

9. Distinction between airplane and other aeronautical vehicles.—Normal surface craft, submarines, and airships, entirely when at rest and principally when underway, depend for sustentation upon the physical fact called the "Principle of Archimedes," namely, that a body submerged in a fluid is buoyed up by a force equal to the weight of the fluid displaced. Ships and submarines are said to be supported by hydrostatic forces, and airships by aerostatic forces. The science dealing with the latter forces is "aerostatics."

a. The aquaplane and the hydroplane, underway, displace much less water than that required to support them and their loads at rest. They are supported principally by hydrodynamic forces. Aircraft, like surface craft, may be supported by static or dynamic forces. Those aircraft supported by static forces such as free balloons, blimps, dirigibles, etc., are called "lighter-than-air" craft or airships. Those aircraft supported by dynamic forces are called "heavier-than-air" craft.

b. Heavier-than-air craft may be classified as ornithopters, helicopters, autogyros, gliders, and airplanes.

(1) The ornithopter is an alleged flying machine that is supported, birdlike, by the flapping of wings. The ornithopter may be compared with the Australian bird called the Kiwi, which runs around flapping its wings but never takes off.

(2) The helicopter is a flying machine supported by the upward thrust of horizontally rotating propellers. Successful types of the true helicopter do not exist at present.

(3) The autogyro is a flying machine having a conventional and conventionally placed engine-propeller unit and is supported by the upward thrust of a large rotor or windmill resembling a propeller

rotating in a substantially horizontal plane, the rotation being effected by the air forces acting upon it. These air forces are caused by the forward motion of the craft through the air. The autogyro is the most successful of the unconventional types and promises to have military value. The autogyro has a number of excellent features in that it can take off with an exceptionally small run, climb very steeply, and cannot be accidentally spun. Its forward speed may be reduced to the point where it will momentarily hover over an object. Its descent may be vertical at a speed as low as a parachute, and it can be landed within "the circle" without rolling out of it. The autogyro does not possess a great deal of speed at present, and maneuverability is practically nil, but its good features are such as to assure its retention and further development as a type.

(4) The glider is simply a lightweight airplane without motor. It is given initial flight by catapulting or towing and once aloft it may glide to the ground or the pilot may ride upward moving air currents. These currents will supply the energy necessary to sustain flight. A glider being supported by updrafts is said to be "soaring" and the machine is often called a "sailplane." The glider is primarily a sporting or training device.

(5) There remains the airplane as the most common, most successful, and most highly developed type of flying machine. It is supported by dynamic forces caused by air being passed over its wings. The relative motion of the air is effected by having the craft forced through the air by an engine-propeller unit.

10. Fundamental conceptions.—The mathematics of aerodynamics is rather deep and involved but for the purpose of this manual it is less pretentious than that of any other branch of engineering.

a. Force is the term applied to the exertion of muscular effort or to any effort which may be employed in lieu thereof. Thus in pushing with the shoulder against a wall a force is exerted.

b. Matter is a term applied to describe objects or substances that occupy space or possess weight and hence muscular effort or some other force is required to support or move them.

c. Weight is the force urging each body toward the ground and exists whether the body be a liquid, gas, or solid. The air itself is matter and hence a given volume will have a definite weight for definite conditions of temperature and atmospheric pressure.

d. Vectors.—Forces, velocities, and other quantities that involve direction as well as magnitude are said to be "vector quantities" or "vectors." Those quantities that involve magnitude alone are called scaler quantities. A vector may be represented by a straight line, the

length of which designates the magnitude of the quantity. An arrowhead on one end indicates the direction of the line of action while the other end constitutes the point of application. Thus a force of 4 pounds applied at *A* and acting toward the right may be represented by the 1-inch line below, where each pound is ¼ inch.

e. Resultant.—(1) The resultant of two vectors is defined as the single vector which will produce the same effect upon a body as is produced by the joint action of the two vectors. Thus if two parallel forces are acting in the same direction their resultant is equal to the sum of the two forces, whereas if they are acting in opposite directions the resultant is equal to the difference between them and acts in the direction of the greater force. If these two vectors, such as two

FIGURE 2.—Representation of a vector quantity.

forces, are not parallel, the resultant will lie within the angle formed by the two vectors and is determined as follows:

(*a*) From the point of application *A*, draw line *AB* in the direction of the first force and of length representing its magnitude to a definite scale;

(*b*) From *A* draw line *AC* in the direction of the second force and of length representing its magnitude to the same scale as *AB*;

(*c*) With lines *AB* and *AC* as two sides of a parallelogram, complete the same in dotted lines;

(*d*) Draw the diagonal from the point of application *A*. This diagonal *AD* represents in magnitude and direction the resultant of the two forces *AB* and *AC*.

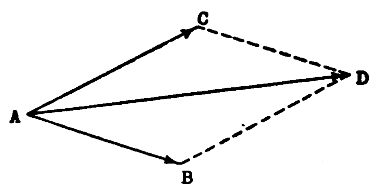


FIGURE 3.—Resultant of two vectors.

(2) As a practical example of the use of vector diagrams, take the case of an airplane flying on a course east at airspeed of 65 m. p. h. Wind from southeast, velocity 25 m. p. h. The resultant of the wind and airspeed velocity vectors will give the vector of the ground speed. Let *A* be the point of departure of the airplane. Draw the wind vector *AB* to scale 25 m. p. h. in direction 315°, the direction in which the wind is blowing from the point of departure. Draw the airspeed vector *AC* to scale 65 m. p. h. Complete the parallelogram *ABCD*. The

diagonal AD is the resultant ground speed, 50 miles per hour in the direction 69°.

(3) Vector diagrams enable the student to solve graphically, with ease and simplicity, problems in forces, velocities, etc., which would otherwise require tedious mathematical calculation. It must be emphasized that accurate results depend upon accurate construction and measurement of the vector diagram.

f. Component of a force.—A force vector will obviously produce a maximum effect along its line of action. Nevertheless, in any other

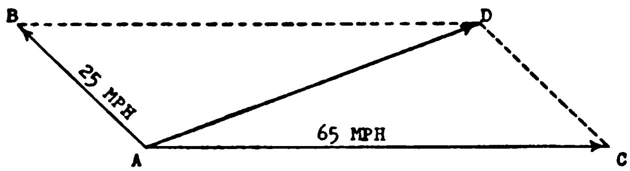


FIGURE 4.—Vector diagram.

direction an effective force is evidenced, this effective force being termed a "component" for the stipulated direction. To find the component of a force in any given direction—

(1) Represent the force by a line such as AB in figure 5;

(2) Using AB as a diagonal, construct upon it a rectangle, the sides AC and AD of which are respectively parallel and perpendicular to the direction of the required component;

(3) The length of the side AC which is parallel to the given direction represents the magnitude of the desired component.

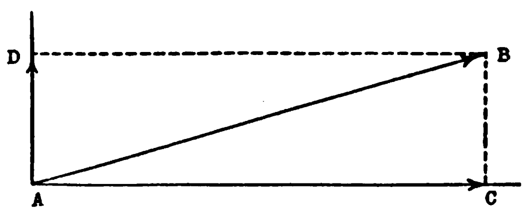


FIGURE 5.—Components of a vector quantity.

11. Moment of a force—equilibrium.—The tendency of a force to produce a rotation around a given axis is called the moment of the force with respect to that axis.

a. The amount and direction of the moment of a force depend upon the direction of the force and upon its distance from the axis. The perpendicular distance from the axis to the line of the force is called the moment arm and the moment is measured by the product of the force and the moment arm. Thus a force of 10 pounds acting at a distance of 2 feet from the axis exerts a turning moment of 20 foot-pounds.

b. In order to distinguish between moments tending to produce rotation in opposite directions, those tending to produce a clockwise rotation are called positive moments; those in the opposite direction, negative moments.

c. If the algebraic sum of the moments is zero, that is, all the positive or clockwise moments equal the negative or counterclockwise moments, there will be no rotation. It is usual to express this in the form $\Sigma M=0$. Σ is the Greek letter sigma and ΣM means the sum of all the moments M both positive and negative.

Taking moments about point A:

M_1 acts in counterclockwise direction force of 1 pound at a distance of 3 feet $=-3$ foot-pounds moment.

$M_2=-4$ foot-pounds.

$M_3=-1$ foot-pound.

$M_4=+8$ foot-pounds.

Then $M_1+M_2+M_3+M_4=-3fp-4fp-1fp+8fp=0$ (1)

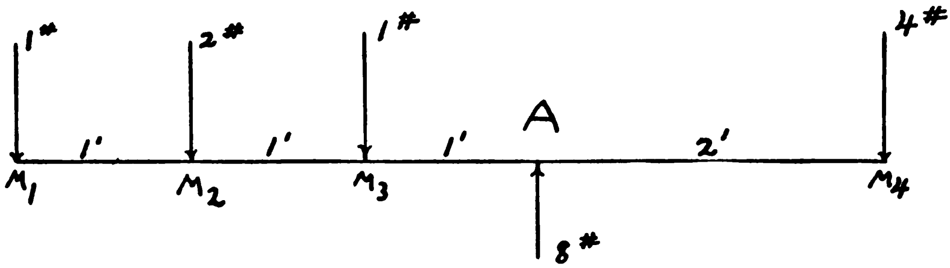


FIGURE 6.—Moment diagram.

or using the usual notation $\Sigma M=0$

Since the moments balance about axis A there is no rotation.

d. There are 8 pounds of force acting down, and unless the axis is supported by an upward force of 8 pounds, there will be downward movement but no rotation. If the total vertical forces equal zero there will be neither rotation nor translation and the body would then be said to be in equilibrium.

Vertical forces acting upward are called positive; those acting down, negative. For equilibrium the algebraic sum of the vertical forces must equal zero. This is indicated by the symbols $\Sigma V=0$.

e. A group of horizontal forces have the same relation and for horizontal balance $\Sigma H=0$.

f. Forces at an inclined angle can be resolved into their vertical and horizontal components as shown in the section on vectors.

Hence the conditions for equilibrium are—

$$\Sigma H=0 \quad \Sigma V=0 \text{ and } \Sigma M=0. \tag{2}$$

g. It is important for the student of aerodynamics to realize that the above conditions for equilibrium hold true if such a system of forces is imposed upon a body (e. g. an aeroplane) which is moving, since the original motion is in no wise affected by this superimposed system.

12. Velocity.—Velocity of a moving body or particle is the distance traveled divided by the time during any particular period. Velocity may be expressed as miles per hour (m. p. h. or mi./hr.), feet per second (f. p. s. or ft./sec.) or any other ratio employing standard units. It is customary in aerodynamics in the United States to use the ratios mi./hr. and ft./sec. as standard.

13. Acceleration.—*a.* If a moving body changes its velocity it is said to accelerate. Acceleration is a rate of change of velocity or the average change in velocity in a given time.

b. The most common example of acceleration is that of a falling body. If a body is dropped in a vacuum its velocity at the start will be zero feet per second. At the end of the first second its velocity will be 32.2 ft./sec. and its acceleration is expressed as (32.2 ft./sec. − 0 ft./sec.)/sec. or 32.2 ft./sec./sec. At the end of the next second its velocity is 64.4 ft./sec. indicating a change in velocity of 32.2 ft./sec. in one second.

c. Accelerations and forces are closely associated, so closely in fact, that it is frequent that in discussing forces reference is made to the acceleration produced rather than to the force itself. This is done for purposes of comparison.

14. Mass.—In dealing with moving bodies it is necessary to use not only the weight of the body but also the acceleration of gravity. This relation is used as a ratio of $\frac{W}{G}$ and is called "mass".

15. Specific gravity—density.—*a. Specific gravity.*—The ratio of the weight of a solid or liquid to the weight of an equal volume of water at some standard temperature is called its specific gravity. The specific gravity of gases is usually referred to hydrogen or air.

b. Density.—(1) The density of a body is its weight per unit volume, example $\frac{W}{V}$.

(2) The mass density is used in discussing moving bodies and is the ratio of mass to volume and is expressed as $\frac{M}{V}$.

(3) In the case of solids the ratio of mass to volume cannot change. This is not the case with gases, however. If a sounding balloon is inflated with air until it has a volume of 2 cubic feet, a definite mass of air will be contained therein. By the heating of

the balloon it can be expanded to about 4 cubic feet. The volume has been doubled but the amount of air trapped within the envelope remains the same. Hence the density of the air is just half what it was before heating. If instead of raising the temperature of the air and thus causing inflation of the balloon, it were compressed until of only 1 cubic foot volume, the density would be twice the initial value. In general, for a given kind of gas, the product of the pressure and volume, divided by the mass and by the absolute temperature is constant or—

$$\frac{PV}{mT}=R \qquad (3)$$

Where P=pressure, V=volume, m=mass, T=absolute temperature and R is a constant depending only on the kind of gas. This is the law of gases and is a combination of two well-known laws of physics, that is, "Boyle's Law" and "Charles' Law".

16. Standard atmosphere.—*a.* A cubic foot of air will weigh more, the greater the atmospheric pressure and the lower the temperature. Since the reaction of the air against an airfoil depends upon the mass of air coming in contact with it, there must be a definite standard for the measurement of mass. The National Advisory Committee for Aeronautics has adopted the following conditions as standard: dry air under a barometric pressure of 29.92 inches of mercury at a temperature of 15° C. A cubic foot of air under these conditions weighs 0.0765 pound. Air containing water vapor is somewhat lighter than dry air.

b. The earth being surrounded by a blanket of air, estimated as more than 200 miles in thickness, it is obvious that with altitude the density must decrease. Increase in altitude leaves less air above to compress that below. Figure 8 shows the relations existing in temperature, relative density, and relative pressure with altitude.

17. Center of gravity.—*a.* Newton's law of universal gravitation states that—any two bodies in the universe attract each other with a force which is directly proportional to the product of the masses and inversely proportional to the square of the distance between them. This holds whether the bodies are two planets or an airplane and the earth. In fact, every particle of any body at or near the earth's surface will be pulled toward the center of this greater mass, and the total force will be equal to the sum of the pulls on the individual particles. This total force is termed the weight of the body and may be considered as acting at a point in the body called the center of gravity.

b. This center of gravity is the point of application of the resultant of all the pulls on individual particles of the body. It may be de-

termined as follows: The body, an airplane, is suspended from a cable clear of the ground. The cable will assume a vertical position and be subjected to a tension equal to the weight of the airplane. The same will hold regardless of the point of attachment of the cable and consequent attitude of the airplane. Since the line of action of the weight of the airplane will be that of the cable in all cases, the point of intersection of the lines of action for two or more attitudes must represent the point of application of the resultant force, namely, the center of gravity. Figure 9 illustrates one method.

18. Graphs.—*a.* The position of a point may be fixed by reference to two known straight lines intersecting at right angles in the same plane, as the point P (OX and OY of fig. 7). Such lines are known as rectangular coordinate axes. The horizontal line OX is called

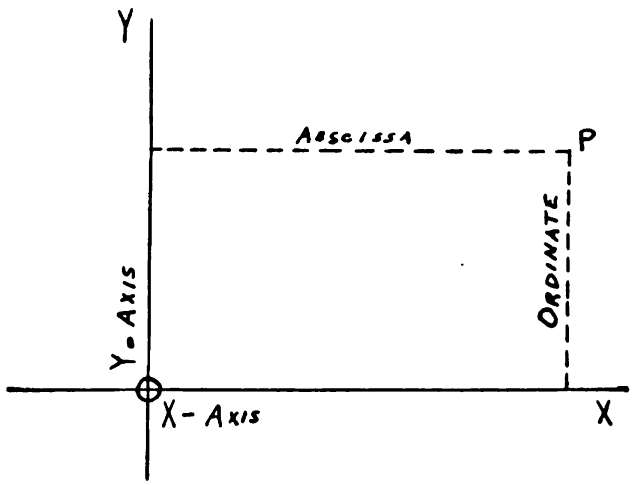


FIGURE 7.—Position with reference to coordinate axes.

the "axis of abscissae" or "X axis." The vertical line OY is called the "axis of ordinates" or "Y axis." The point of intersection is called the origin. The abscissa of a point is its horizontal distance from OY; its ordinate is its vertical distance from OX. These given, the position of the point is determined. A familiar example of plotting the position of a point by reference to coordinate axes is the latitude and longitude of a point on a Mercator Chart.

b. A succession of points may be plotted with reference to coordinate axes and these points connected by a smooth line, thus forming a curve. Such curves are frequently the most convenient and the clearest way of representing some physical relation. For convenience squared or cross section paper is used for this purpose. A typical example is that shown in figure 8.

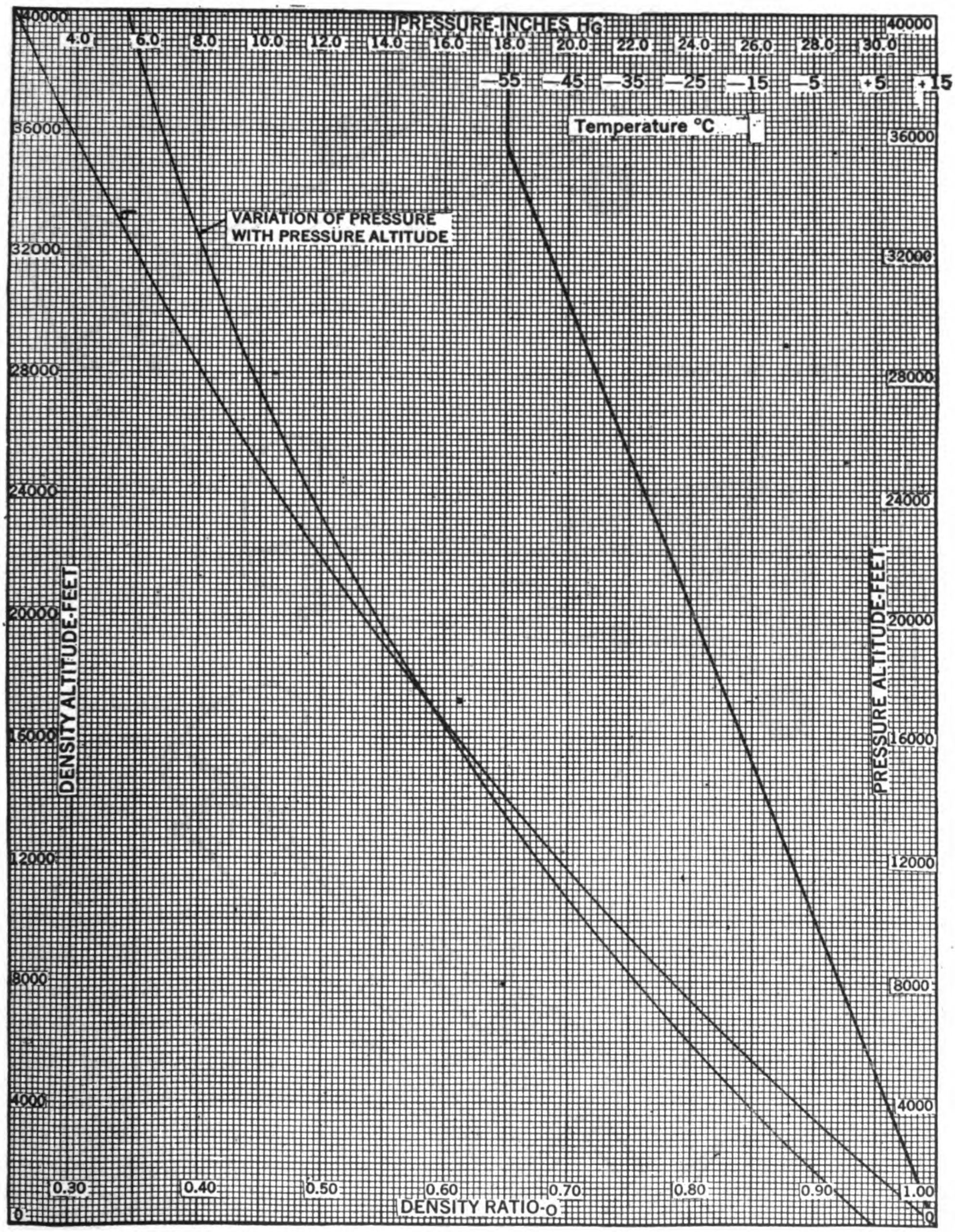


FIGURE 8.—Standard atmosphere.

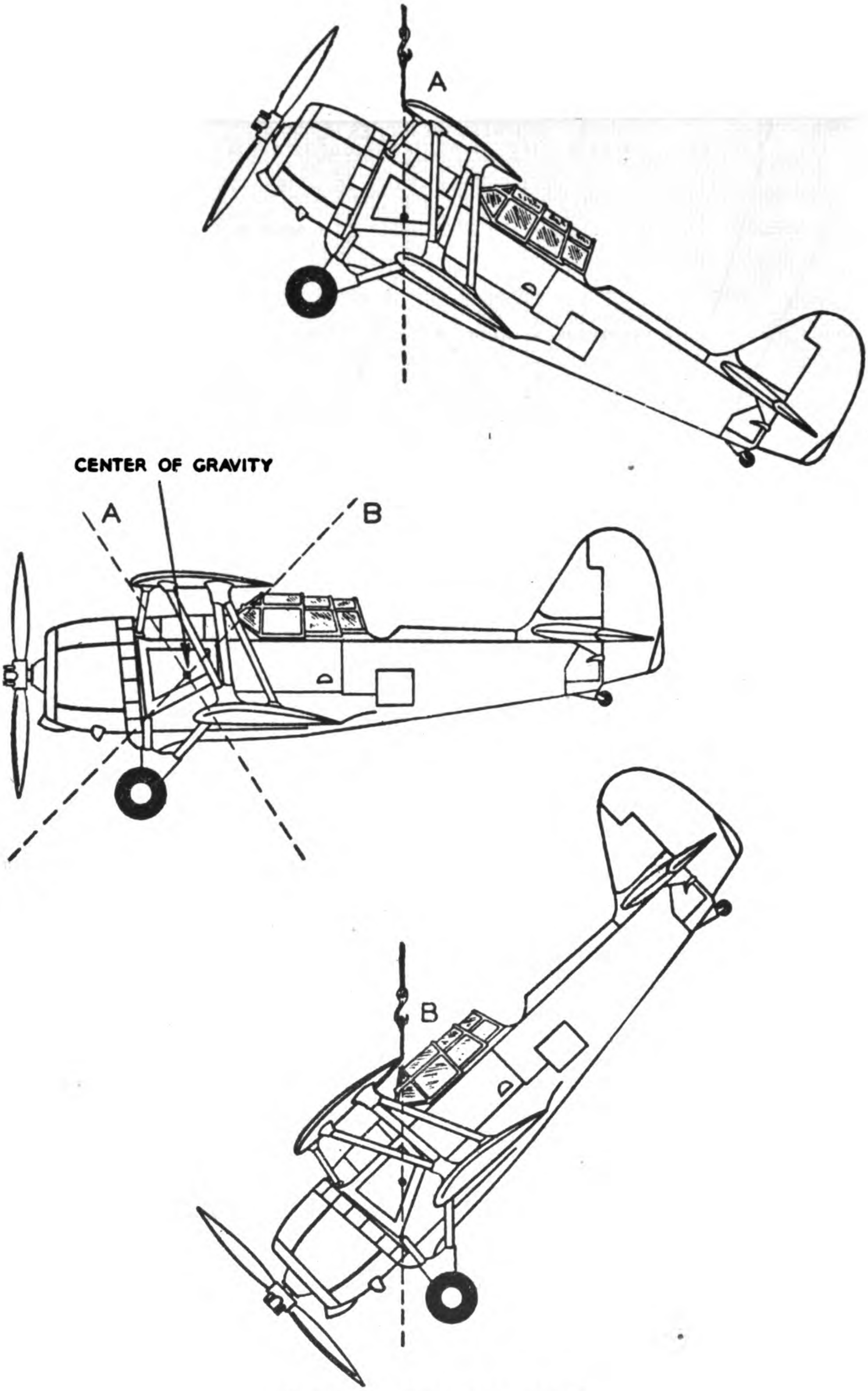


Figure 9.—Center of gravity.

19. Relative motion.—*a.* If a body changes its position it is said to be in motion. The position of the body is fixed by its distance from surrounding objects. Hence, a body which has moved has changed its position with respect to some other object regarded as fixed. In other words, there has been relative motion. A person sitting quietly in a Pullman seat may be said to be not moving though the train is traveling at 60 miles per hour. Here the individual is at rest with respect to the Pullman in which he is riding though the train itself is rushing rapidly over the earth's surface which is considered as fixed in stating the velocity over the ground.

b. So it is with objects sustained in the air. On a calm day a balloon will maintain a fixed position over its point of departure from the ground. With a wind blowing it is carried away from the point of departure at a velocity equal to that of the wind. There is no relative motion between the balloon and the wind if it maintains its altitude but there is between the balloon and the ground. The airplane, on the other hand, depends for its sustentation on relative motion between itself and the surrounding air. This relative motion is expressed as the airspeed. On a calm day an airplane requiring an airspeed of 60 m. p. h. to maintain itself in flight will leave the point of departure at this velocity. If headed into a 60 m. p. h. wind, the airplane will remain over its point of departure or will have zero ground speed, that is, no relative motion between the airplane and the ground.

c. Since all motion is relative, velocity which fixes the rate of motion is also relative, and a body may have at the same time different velocities (either in amount or direction) with respect to different bodies. Thus, an airplane flying at 60 m. p. h. airspeed against a 20 m. p. h. breeze will have a velocity of 60 m. p. h. with respect to the air and a velocity of 40 m. p. h. with respect to the ground.

20. Momentum.—A body moving at uniform velocity by reason of its inertia (resistance to change of motion) tends to continue at uniform velocity. This tendency is called momentum and is measured by the product of the mass and its velocity. This momentum can only be changed by the application of some external force to the body. When the force is applied to the body, its mass will not change, hence the velocity must change.

21. Newton's laws of motion.—*a.* Newton has given as three laws of motion:

(1) Every body tends to remain in a state of rest or of uniform motion in a straight line except insofar as it is acted upon by an impressed force.

(2) Change of momentum is proportional to the impressed force and to the time during which it acts and takes place in the line of action of that force.

(3) To every action there is an equal and opposite reaction.

A clear understanding of these laws is absolutely essential to the study of aerodynamics.

b. The first law is generally spoken of as the law of inertia. It simply means that a body at rest will not move unless force is applied to it. If it is moving at uniform speed in a straight line, force must be applied to increase or decrease that speed.

c. The second law means that if a body moving at uniform speed is acted upon by an outside force, the change of motion will be proportional to the magnitude of the force acting, and the new direction of motion will be the resultant of two components, one the original motion the other that produced in the line of action of the force. Mathematically the law may be expressed by—

$$kF = Wa \tag{4}$$

where F, a force acting on a mass W, produces a rate of change of motion (acceleration) a, and k is a constant depending on the units used to measure F, W, and a. By experiment it may be determined that $k=g$, the acceleration of gravity, and the equation therefore becomes—

$$Fg = Wa \tag{5}$$

Many persons are irritated by the presence of the multiplier g and get rid of it by using an artificial unit of force, the poundal. In this system the poundal$=1/g$ pounds and the equation is written—

$$F \text{ (poundals)} = W \text{ (pounds)} \times a \tag{6}$$

Another way of concealing the multiplier g is to measure the forces in the common pound unit, but to adopt an artificial unit of mass, the slug. In this system, the slug$=g$ pounds, and the equation is written—

$$F \text{ (pounds} = \frac{W \text{ (pounds)}}{g} \times a = m \text{ (slugs)} \times a \tag{7}$$

The National Advisory Committee on Aeronautics customarily uses the slug as the unit of mass and the pound as the unit of force. This system of units will be used in this manual, but the student must always be aware that g lurks in the background and will appear and disappear in a most confusing manner.

d. The third law is well exemplified by the action of a swimmer's hands. He pushes water aft and thereby propels himself forward, since the water resists the action of the hands. The action of the 16-inch gun is likewise typical. On being fired the mass of the gun

times the velocity of recoil will equal the mass of the shell times its velocity. In general, when one body acquires momentum in one direction another body will acquire an equal and opposite momentum.

22. Dynamic reaction of airstream.—*a*. Since air possesses mass and inertia, a stream of air moving in a certain direction at a certain velocity will, according to Newton's first law of motion, continue to move in the same direction at the same velocity until some outside force is exerted against it. If a flat plate is held normal to an airstream, the air impinging upon the plate must change both its immediate direction and velocity to pass around the plate. The plate exerts a force against the airstream and the latter, in accordance with Newton's third law, exerts an equal and opposite force against the plate. The equilibrium of these forces, as indicated in figure 10, will be maintained as long as the relative motion is maintained constant; in this case as long as the plate is held in position.

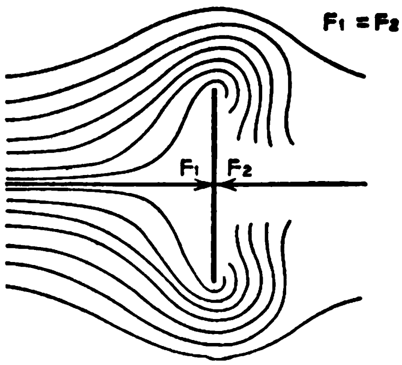


FIGURE 10.—Airflow about a flat plate normal to the wind.

b. If the plate, on the other hand, were moved through still air at a rate sufficient to produce the *same relative motion* the force required to move the plate through the air would equal that previously required to hold it in position, while the resistance offered by the air to the moving plate would equal the force previously exerted by the impinging airstream.

c. Should the plate be held at an acute angle to the relative wind a similar condition must hold, that is, the plate will produce a dynamic reaction. The air is pushed downward and its velocity reduced by the interference of the plate. Hence, the plate must exert a force on the air downward and forward. The reaction of the air must be an equal pressure upward and backward as shown by the vector *AR*. The vectors *AL* and *AD* are respectively the vertical and horizontal components of the pressure of the airstream against the plate. In order to maintain the relative motion between air and plate there must be a

downward force AL_2 equal to the upward force AL_1 and a forward force AD_2 equal to the backward force AD_1.

23. Streamline flow and turbulence.—*a.* If a thin flat plate is held edgewise to an airstream, as shown in figure 12, the air will part at the leading edge and flow smoothly over the upper and lower surfaces, reuniting abaft the trailing edge. The resistance offered

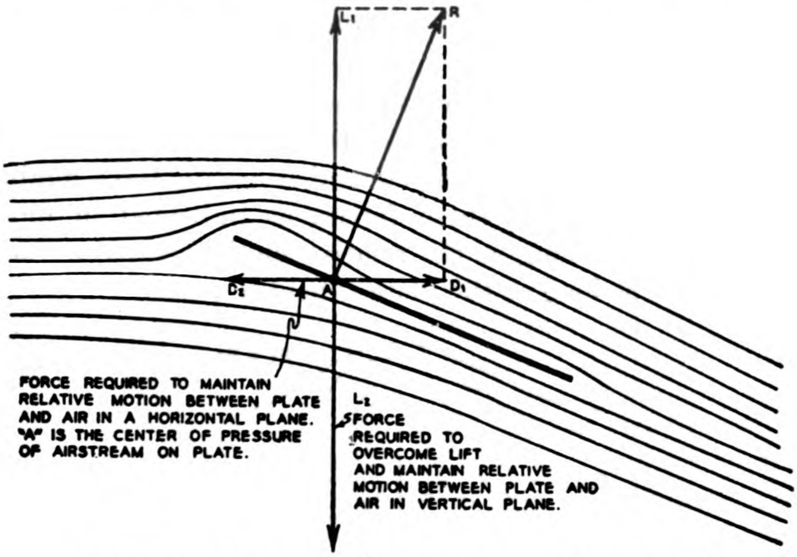


FIGURE 11.—Airflow about a flat plate inclined to the wind.

will be small, consisting largely of skin friction caused by the air tending to cling to the surfaces of the plate owing to the viscosity of the fluid and roughness of the surface. Some turbulence, however, will result, for the velocity of streamlines adjacent to the plate will be cut down, and, in consequence, a given volume of such air will have a greater cross sectional area causing a spread in

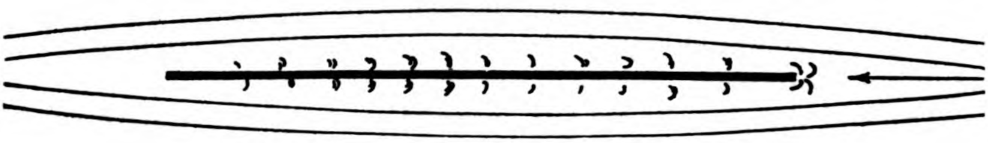


FIGURE 12.—Airflow about a flat plate edgewise to the wind.

contiguous streamlines or layers. These diverging streamlines must converge behind the trailing edge even though the plate thickness is infinitesimal. This bowing of streamlines due to setting up a velocity gradient will set up eddies in the flow of air or produce turbulence. The resulting eddies are so infinitesimal, however, that they constitute little drag or resistance and the flow is said to be

streamline. This is the case with certain forms other than the thin flat plate edgewise to the wind. Such forms are called "streamline" forms since they offer a minimum disturbance to otherwise parallel or streamline flow. A typical streamline form is shown in figure 13.

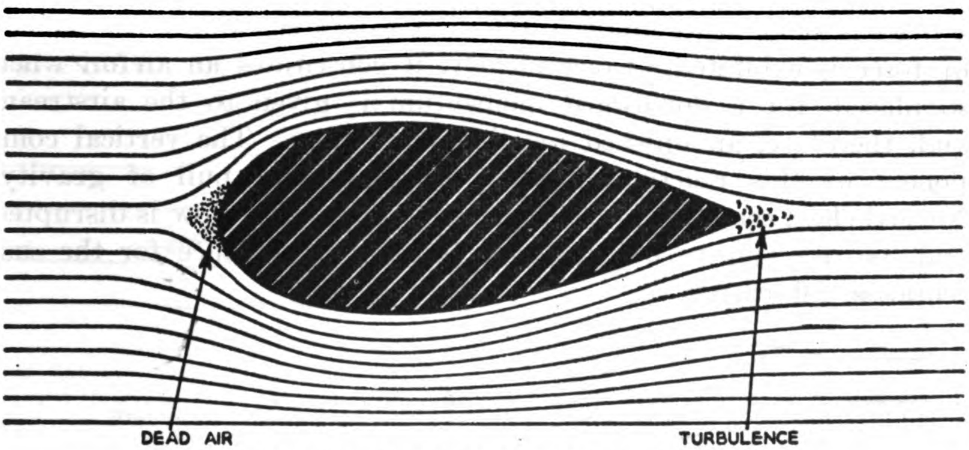


FIGURE 13.—Airflow about a streamline form.

b. If a flat plate, instead of being held edgewise to an airstream, is held at right angles to it as shown in figure 14, a maximum disturbance to linear flow will result. Here the skin friction becomes negligible while the eddy making resistance or turbulence reaches

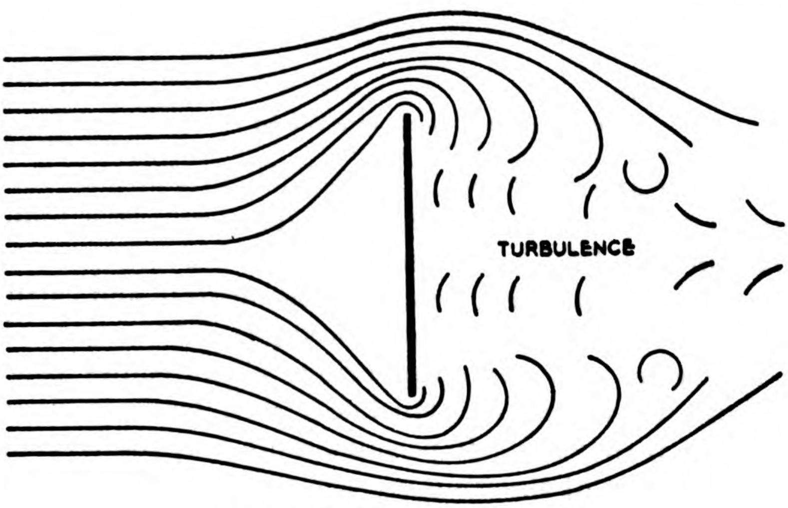


FIGURE 14.—Turbulent airflow.

an excessive value. Both the velocity and direction of the streamlines are abruptly varied with consequent eddying or "burbling."

24. Airfoil.—*a.* In dynamic reaction, streamline flow, and turbulence (par. 22 and 23) lie the elements vital to the airfoil. An air-

foil is a surfaced body which responds to relative motion between itself and the air with a useful dynamic reaction. While a flat plate perpendicular to an airstream will produce dynamic reaction it is in no wise useful owing to the turbulence created and complete absence of a component of force offering sustentation. When such a plate is at an acute angle to the airstream a sustaining component of force is exhibited. Consequently, it constitutes an airfoil when so placed, for a downward momentum is given to the airstream and, therefore, an upward reaction must exist. The vertical component of this reaction opposes the downward pull of gravity. Nevertheless, the plate is inefficient since streamline flow is disrupted and the resulting turbulence offers excessive resistance for the sustentation afforded.

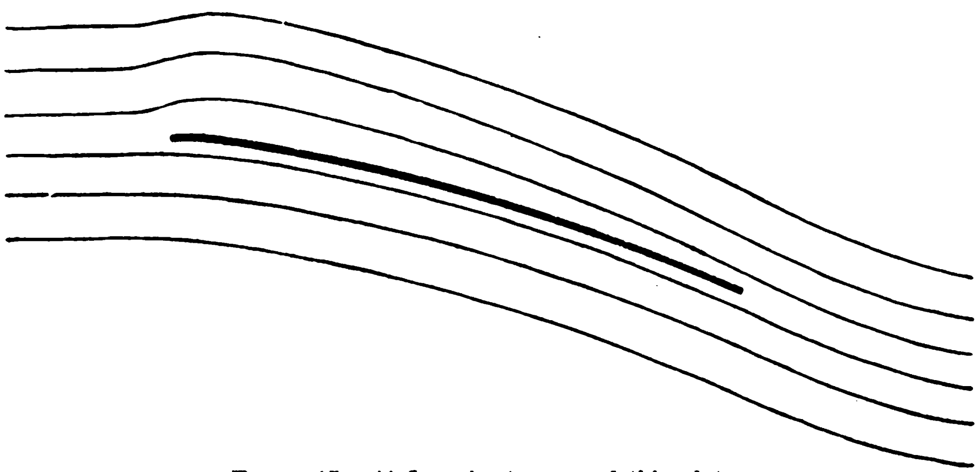


FIGURE 15.—Airflow about a curved thin plate.

b. Curvature and thickness are paramount requisites for an efficient airfoil, that is, one in which the sustaining force is high for the price paid in skin friction and turbulence. Curvature is of marked assistance toward improving downward momentum and cutting down turbulence at the leading edge at high angles. At very small angles to the airstream such curvature brings about eddies beneath the leading edge as indicated. Thickness then becomes desirable to eliminate this turbulence. It permits, moreover, the housing of the structural members of the wing beneath the surfaces. A typical airfoil section is shown in figure 17.

25. Reaction of air upon airfoil.—*a*. The resultant dynamic reaction upon an airfoil being a force accompanying a change of momentum of the air affected, Newton's second law of motion is directly applicable to the determination of its magnitude. This force de-

pends upon the mass of air deflected by the airfoil and the acceleration imparted to that mass of air.

b. Referring to figure 18, an airstream of cross section area S sweeps across a line PQ and in time t reaches line $P_1\ Q_1$ a distance l, behind PQ. The volume of air passing PQ in this time is $S \times 1$. Since the velocity of the airstream, $V = 1/t$, the volume may be expressed as—

$$\text{Vol.} = S \times V \times t \tag{8}$$

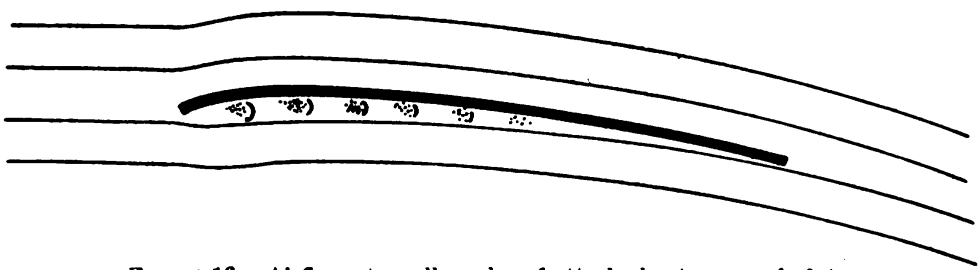


FIGURE 16.—Airflow at small angles of attack about a curved plate.

The density of the air, ρ = mass/volume, from which

$$\text{m (mass)} = \rho \text{ vol.} = \rho SVt \tag{9}$$

If an airfoil be placed at line PQ deflecting this mass, an acceleration a will be imparted. In accordance with Newton's second law,

$$F \text{ (force)} = kma$$

The resultant reaction: $F = k\rho SVt \times V/t = K\rho SV^2$ (10)

FIGURE 17.—Airflow about an airfoil.

If a single coefficient is employed to account for the formula dimensions, the airfoil shape, and its attitude with respect to the airstream a simplified equation results:

$$F = KSV^2 \tag{11}$$

26. Lift and drag.—*a*. The resultant reaction on an airfoil placed in an airstream is designated by the vector OR in figure 19. The point of application O is the center of pressure or the point at which

the aerodynamic forces may be considered as concentrated, for purposes of computation. Its abbreviation is c. p. The c. p. is assumed to be on the chord, a straight line, extended if necessary, brought into contact with the lower surface of the section at two points. In the case of an airfoil of double convex curvature the chord is a straight line between the leading and trailing edges.

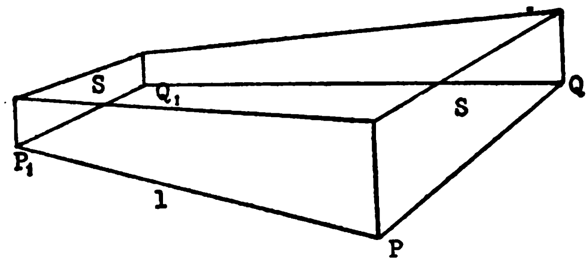


FIGURE 18.—Diagrammatic airflow.

b. The direction and point of application of OR depend upon the shape of the airfoil section and the angle at which it is set to the airstream. The acute angle between the chord of the airfoil and the relative wind is called the "angle of attack."

c. The magnitude of OR has been determined to be KSV^2. Consequently, the components of the resultant reaction parallel and perpendicular to the relative wind will have values differing only in the coefficients. The component perpendicular to the relative wind, des-

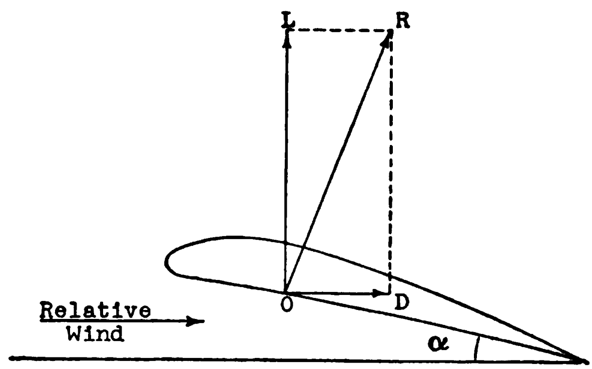


FIGURE 19.—Forces acting on an airfoil.

ignated by OL, is termed "lift," L. The component parallel to or in the line of action of the relative wind, designated by OD, is termed the "drag" D. Hence:

$$L = K_y S V^2 \tag{12}$$

$$D = K_x S V^2 \tag{13}$$

where K_y and K_x are constants such that if S be expressed in square feet and V in miles per hour, L and D will be respectively the lift

and drag in pounds. The lift provides the necessary sustentation overcoming the force of gravity or weight of the airplane. The thrust of the propeller is utilized to overcome the drag of the wings and other parts of the airplane and to maintain the relative motion needed for lift or sustentation.

27. Units and dimensional relations.—*a.* All mechanical and nearly all physical quantities may be defined in terms of three arbitrarily selected units, not dependent on any other units. These are called *fundamental units*, and the others, defined with reference to them, *derived units*. It is customary to choose as fundamental the units of *length, force, and time.*

b. An analysis of derived units with reference to the fundamental units is given in the following table.

TABLE I

Names of quantities	Dimensional formulas	Foot-pound (force) second
Length	L	foot (ft.)
Force	F	pound (lb.)
Time	T	second (sec.)
Velocity	LT^{-1}	ft./sec.
Acceleration	LT^{-2}	ft./sec.^{2}
Angular velocity	T^{-1}	rad/sec.
Angular acceleration	T^{-2}	rad/sec.^{2}
Mass	$L^{-1}FT^2$	"slug" (sl.)
Weight	F	lb.
Moment of mass	FT^2	sl-ft.
Moment of inertia (body)	LFT^{-2}	sl-ft.^{2}
Moment of force	LF	ft. lb.
Work	LF	ft. lb.
Energy	LF	ft. lb.
Power	LFT^{-1}	ft. lb./sec.
Momentum	FT	lb. sec.
Density (mass)	$L^{-4}FT^2$	sl/ft.^{3}
Viscosity μ	FTL^{-2}	lb. sec./ft.^{2}
Viscosity, kinematic ν	$T^{-1}L^{+2}$	ft.^{2}/sec.

c. To the student of aerodynamics, a knowledge of the theory of dimensions is of the greatest value as a help to a clear understanding of the relations between physical quantities. Whenever an equation is written between physical quantities the terms of the two sides of the equality must be equal not only in magnitude but in quality, that is, in dimensions. Dissimilar things are never equal and can-

not be added to or subtracted from one another, though they may be multiplied as in the case in obtaining momentum from mass and velocity, or divided as in the case of density. By substituting the dimensional relations in physical equations and testing the result for equality, it is often possible to detect careless errors in analysis.

28. Absolute system.—The absolute system of units and dimensions used by the N. A. C. A. has the advantage that the force and moment coefficients are dimensionless and do not change with the density of the air. The formulas for lift and drag in the absolute system, as used by the N. A. C. A., are as follows:

$$\text{Lift}=\text{coefficient } (C_L)\times\tfrac{1}{2}\text{ mass density of air}\times\text{area}\times\text{velocity}^2 \quad (14)$$

$$\text{Drag}=\text{coefficient } (C_D)\times\tfrac{1}{2}\text{ mass density of air}\times\text{area}\times\text{velocity}^2 \quad (15)$$

Lift and drag are in pounds, density of air is in slugs per cubic foot, area is in square feet, and velocity is in feet per second.

(The term "slugs per cubic foot" is expressed as the weight of a cubic foot of air divided by the acceleration of gravity=32.2 ft./sec.^{2} For example, a cubic foot of air under standard conditions weighs 0.0765 pound and has the value of $\frac{0.0765}{32.2}$ or 0.00238 slug).

The quantity ($\frac{1}{2}$ mass density of air×velocity^2) is known as the "dynamic" or "impact" pressure per unit of area. The lift and drag could be written—

$$\text{Lift (or drag)}=\text{coefficient}\times\text{area}\times\text{impact pressure} \quad (16)$$

29. Engineering system.—In the engineering system, the lift and drag formulas are written as follows:

$$\text{Lift}=K_y\times\text{area}\times\text{velocity}^2 \quad (17)$$

$$\text{Drag}=K_x\times\text{area}\times\text{velocity}^2 \quad (18)$$

Lift and drag are in pounds, area in square feet, and velocity in miles per hour. This system results in the use of units that are more familiar to the student through everyday experience, but the practice of the N. A. C. A. will be followed in this manual in the use of the absolute system.

30. Nature of lift.—It has been demonstrated that lift is the result of downward momentum given to an airstream by an airfoil and the amount of lift is determined by the equation—

$$L=C_L\frac{\rho}{2}SV^2 \quad (19)$$

It remains to examine further the flow of air about the airfoil and to account for the distribution of pressure about the section.

a. When an airstream encounters an airfoil it is bound to separate regardless of the angle of attack. The plane along which the split occurs depends on the angle of attack, for this determines the part of the leading edge which initially influences the airstream, and on which an impact pressure is impressed due to its being at right angles to the flow. At this point on the nose, or leading edge of the airfoil, the relative velocity is reduced to zero and a dead air-space results. For the particular angle of attack, the streamlines will diverge well ahead of the nose much as the bow wave of a ship spreads in advance of the hull. There is this marked difference,

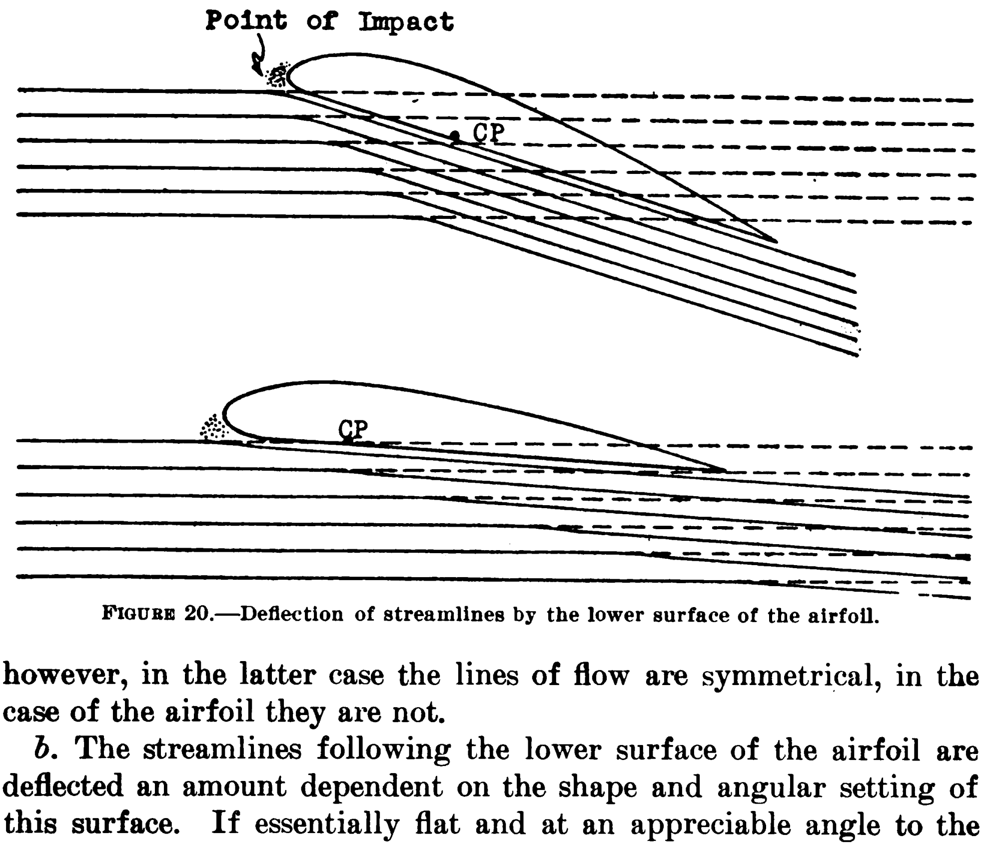


FIGURE 20.—Deflection of streamlines by the lower surface of the airfoil.

however, in the latter case the lines of flow are symmetrical, in the case of the airfoil they are not.

b. The streamlines following the lower surface of the airfoil are deflected an amount dependent on the shape and angular setting of this surface. If essentially flat and at an appreciable angle to the relative wind, the particles impinging nearest the point of impact will hug the surface. Through interference, those adjacent are deflected in advance of where they would otherwise strike, and the net result is that the streamlines are deflected downward for a considerable distance from the airfoil. As the angle of attack is decreased, the deflection becomes less and consequently the augmented pressure decreases. Furthermore, the curvature of the streamlines will be

most pronounced further forward, indicating that the center of pressure on the surface moves forward. With the section at a small negative angle of attack, downward deflection obviously no longer obtains. On the other hand, at excessively high angles of attack, there will be pronounced downward deflection but the airstream will break at the trailing edge and curl forward over the upper surface in a decided eddy.

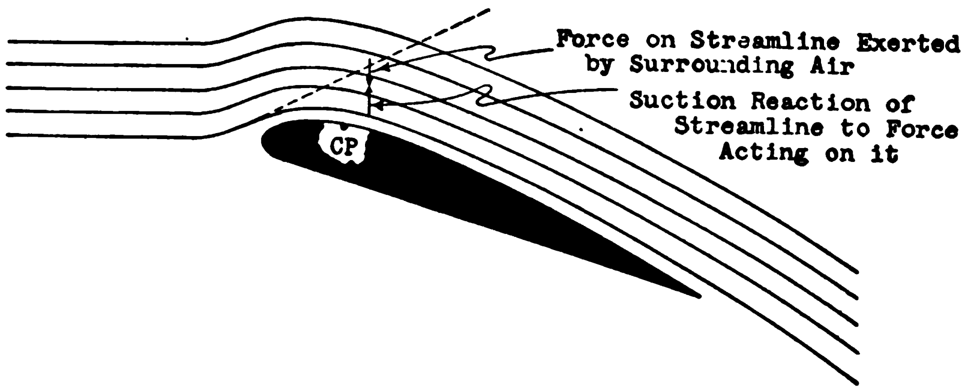


FIGURE 21.—Deflection of streamlines by the upper surface of the airfoil.

c. A different situation exists with regard to streamlines following the upper surface. The streamline adjacent to the point of impact is deflected upward by encountering a portion of the leading edge. Once deflected, it would naturally follow a straight line since the airfoil section no longer exerts a force on it. That it does not follow such a line is due to its encountering the covering blanket of air. This blanket exerts a downward force on the streamline

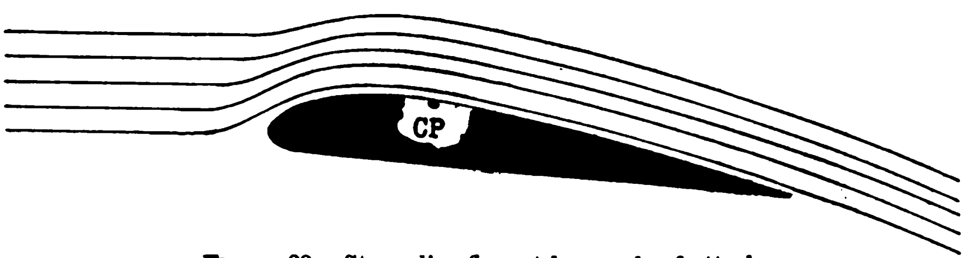


FIGURE 22.—Streamline flow at low angle of attack.

causing it to follow the upper surface. But an equal and opposite reaction must be exerted by the streamline in accordance with Newton's third law. This force is away from the surface and hence produces a suction with respect to it. The adjacent streamlines are initially deflected as in the case of the under surface with consequent building up of a positive pressure on the nose but they likewise are forced to follow the upper contour and hence contribute to the suc-

tion, though to a smaller and smaller extent the more remote they are. With decrease in angle of attack the deflection of the streamlines is initially not as marked and, consequently, the magnitude of the suction is not so great. Furthermore, the resultant will be further aft since here will be found the most pronounced curvature of the streamlines. At very high angles of attack the air blanket exerts insufficient force to have the streamlines follow the surface of the airfoil. In breaking away from the surface, pronounced burbling results which is augmented by the eddies curling up over the trailing edge. As a result the lift is greatly impaired.

31. Pressure distribution.—In paragraph 30 it has been shown that a relatively high pressure to that of the uninterrupted airstream

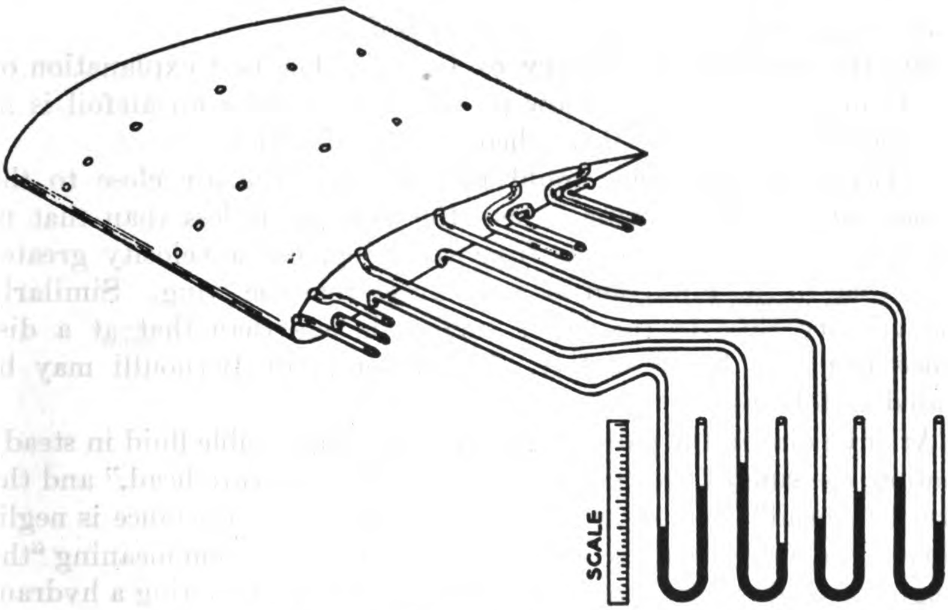


FIGURE 23.—Measurement of pressure distribution.

exists on the under side of the airfoil, whereas a relatively low one, or suction, exists above it. Just how the pressure is distributed may be determined either by model or by free flight test in a manner shown schematically in figure 23.

a. Parallel rows of small static pressure tubes are installed at right angles to the leading edge of the wing and flush with the upper and lower surfaces. These are connected by means of rubber tubing to manometers located outside the experimental chamber of the wind tunnel or in the cockpit of the airplane as the case may be. For any angle of attack, readings of the manometers will indicate the pressure at the respective points, and plots of distribution both

along the chord and from centerline to wing tip can be made. Typical plots of distribution along the chord for different angles of attack are shown in figure 24.

b. Over the bulk of the flight range it should be noted that the suction or relatively low pressure above the airfoil constitutes from 60 to 80 percent of the lifting force. As the angle of zero lift is approached, that is, the attitude in the vertical dive with angle of attack negative, a down load is exerted on the leading edge while the remaining distribution of pressure is such that the resultants for the upper and lower surfaces constitute a pure couple imposing a down load on the front spar and an up load on the rear. Of interest also is the region of high suction at large angles of attack, for it is this suction which is responsible for the opening of the automatic wing slots which are later described.

32. Hydrodynamic theory of lift.—*a.* The best explanation of the formation of high and low pressure areas about an airfoil is in the application of some of the theories of hydraulics.

b. Bernoulli's theorem would indicate that the air close to the upper surface of the wing, where the pressure is less than that in the air at a greater distance from the wing, has a velocity greater than that in the airstream at a distance from the wing. Similarly the velocity close to the lower surface is less than that at a distance from the lower surface. The theorem of Bernoulli may be stated as follows:

At any point in the path of flow of an incompressible fluid in steady motion, the sum of the "potential head," the "pressure head," and the "velocity head" is constant provided the frictional resistance is negligible. The term "head" is an old millwright's expression meaning "the height through which a mass of water descends in actuating a hydraulic machine". It designates the energy of the fluid. Mathematically the theorem is—

$$H=h+\frac{P}{\rho g}+\frac{V^2}{2g} \tag{20}$$

where H if constant, h the potential head, $\frac{P}{\rho g}$ the pressure head, and $\frac{V^2}{2g}$ the velocity head.

(1) For the purpose at hand, justification for high and low pressures about an airfoil, it is sufficient to say "where the pressure is high the velocity is low, and vice versa".

(2) Such being the case, there will be an augmented velocity in the streamlines above the airfoil over that of the uninfluenced airstream

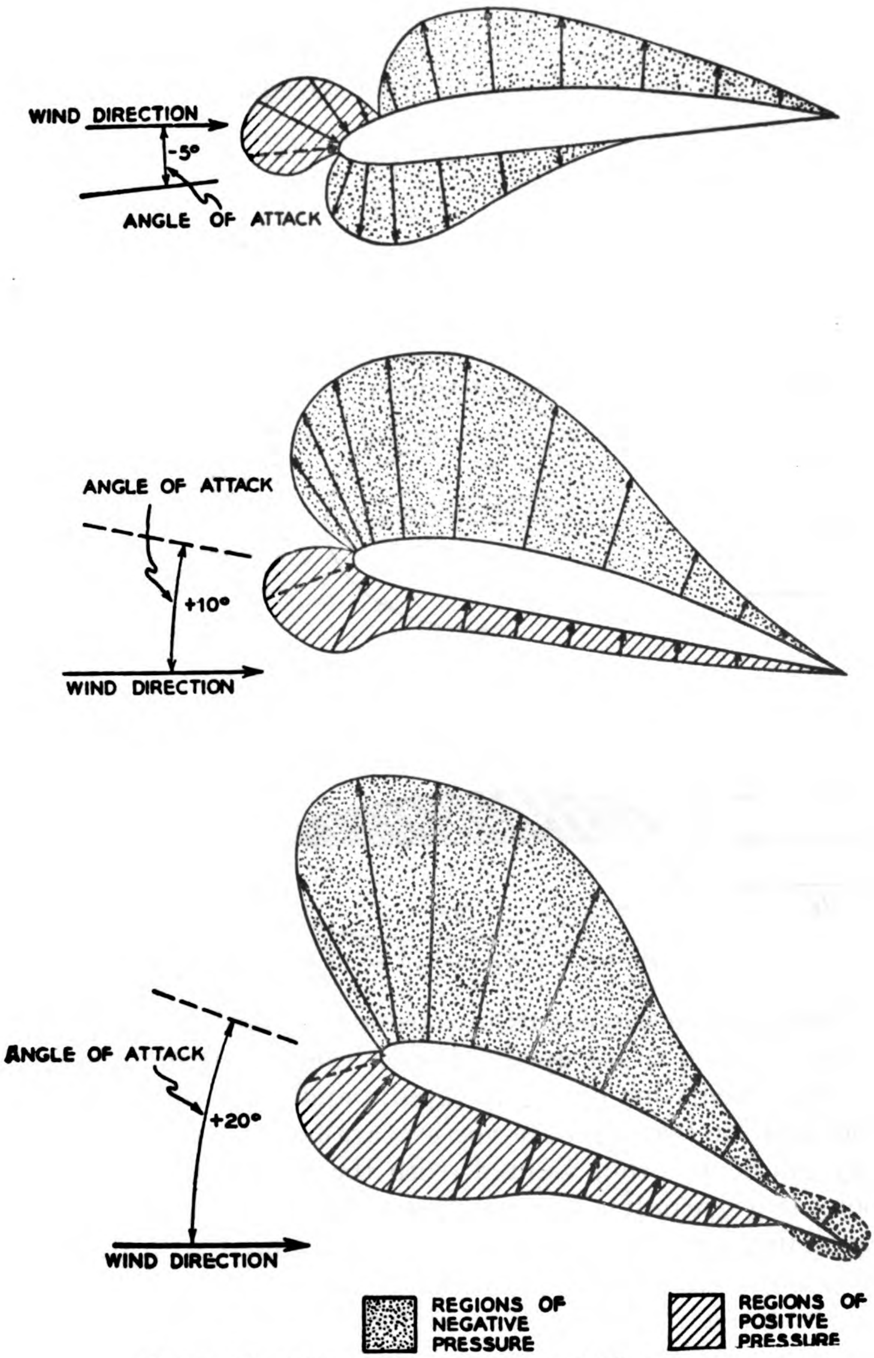


FIGURE 24.—Pressure distribution on airfoil surface.

and a decreased velocity in those below. This velocity variation is easily accounted for if a circulatory airflow about the airfoil is conceived which may be superimposed on that of the natural flow of the airstream as shown in figure 25.

(3) The potential head will not vary materially for any flight condition and hence may be eliminated from the equation for total head The equation then becomes—

$$H=\frac{P}{\rho g}+\frac{V^2}{2g} \tag{21}$$

(4) That such a circulation is not farfetched and both can and probably does exist is evidenced by wind tunnel tests. As the airstream initially encounters the airfoil a succession of small vortices are formed

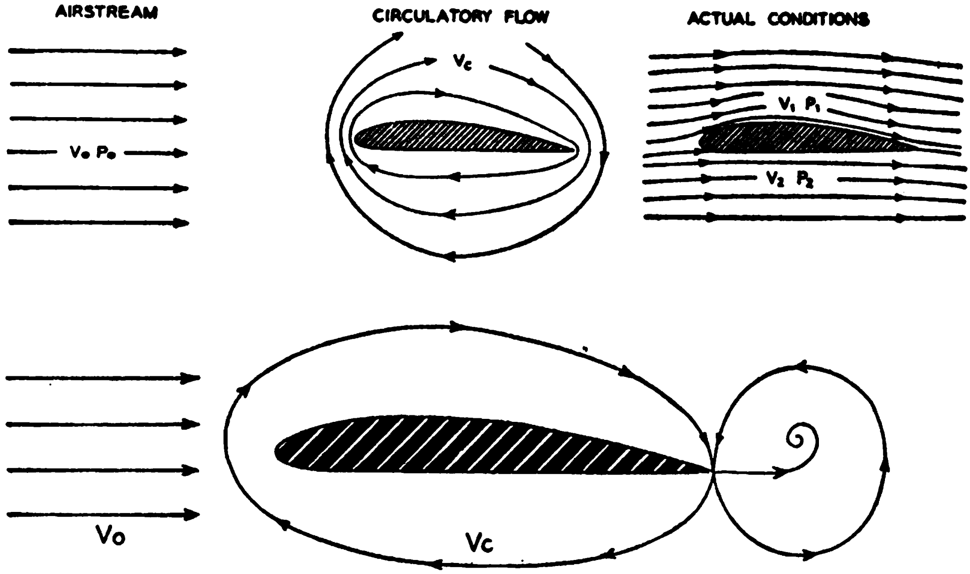


FIGURE 25.—Circulation about airfoil.

at the trailing edge which curl upward and toward the leading edge. These are assumed to set up the desired counter circulation as indicated. The circulation builds up rapidly and when steady conditions are obtained the trailing edge vortices are no longer perceptible. A velocity gradient is thus assured, with the instantaneous velocity at any point in a streamline the resultant of V_o and V_c at that point. A corresponding pressure gradient will be evidenced with distribution such as depicted in paragraph 31.

33. Drag.—*a.* The drag of an airfoil or the resistance it offers to passage through the air for range of angle of attack between zero lift and angle at which the lift ceases to increase in direct proportion to the angle of attack is considered as composed of two parts: profile drag and induced drag.

(1) *Profile drag* is the resistance encountered by virtue of forcing an object through a viscous fluid tending to stick to any object immersed in it. Structural drag, form drag, and the various components of parasite drag are all of the same nature as profile drag.

(2) *Induced drag* is the necessary evil encountered in producing lift. The reaction upon an airfoil, being at an agle to the relative wind, has necessarily a component parallel to the relative wind. This component is called "induced drag."

b. The drag of an airfoil as commonly discussed is the sum of the induced drag and the profile drag.

34. Wind tunnel.—*a. General.*—(1) A wind tunnel is essentially a venturi tube or meter, used originally for the measurement of the flow of water in pipes. The device consists of a conical nozzlelike reducer *AB*, shown in figure 26, at the small end of which is a short cylinder *BC*, called the "throat." To the other end of this throat is attached a conical enlargement *CD* which attains the same size as the inlet *A*, but more gradually.

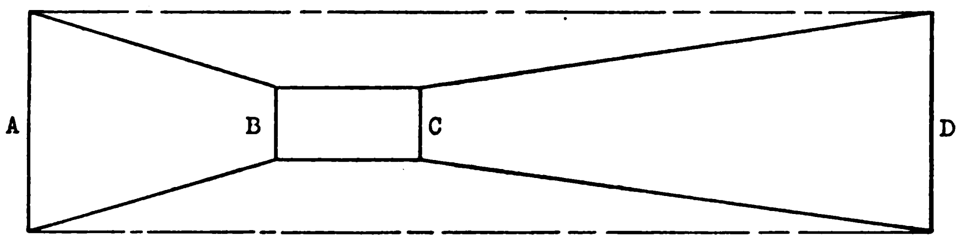


FIGURE 26.—Venturi tube.

(2) The underlying principle is based on the theorum of Bernoulli. The quantity of fluid, water or air, which is drawn through inlet *A* will be discharged through the same sized opening *D*. The velocity of the fluid must, therefore, increase as it is drawn through the inlet cone, attain a maximum value in the throat, and thereafter gradually slow down to its initial value at the outlet. The static pressure in the throat is consequently less than that at the entrance.

Applying the theorum:

$$h_1+\frac{P_1}{\rho g}+\frac{V^2_1}{2g}=h_2+\frac{P_2}{\rho g}+\frac{V^2_2}{2g} \qquad (22)$$

where the subscripts 1 and 2 designate conditions at the inlet and throat respectively. $h_1=h_2$ in the case where the center of flow is horizontal. Consequently

$$\frac{V^2_2}{2g}-\frac{V^2_1}{2g}=\frac{P_1}{\rho g}-\frac{P_2}{\rho g} \qquad (23)$$

Since the difference in pressure heads is measurable directly by manometer and since the cross section areas at the inlet and throat are known, the manometer may be calibrated directly to read the throat velocity. This is the unknown which it is desired to measure in the case of the wind tunnel.

b. Types.—(1) The simplest type of wind tunnel is a venturi tube having refinements aimed to reduce friction losses and insure straight line flow through the experimental chamber or throat. Figure 27 illustrates the essential part of a simple wind tunnel and shows the desirable variations from the venturi meter described above. Air is sucked through the wind tunnel by the propeller fan at the outlet at a definite velocity. A system of balance is employed to measure

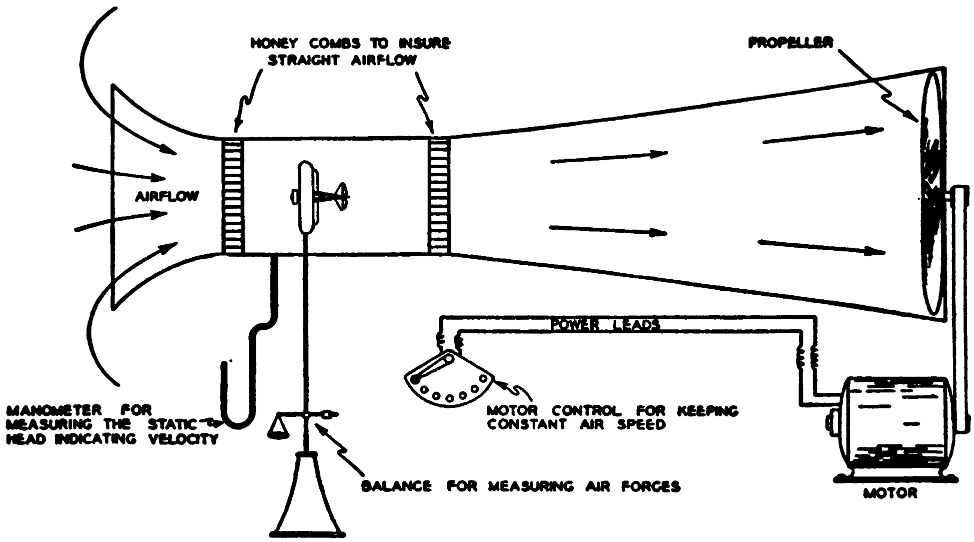


FIGURE 27.—Simple wind tunnel.

the forces required to maintain the model in equilibrium. All wind tunnels have the following in common:

(*a*) A large venturi tube to give a uniform airflow with high velocity in the throat.

(*b*) A power driven propeller.

(*c*) A honeycomb grill to insure a uniform flow of air with parallel streamlines in the throat.

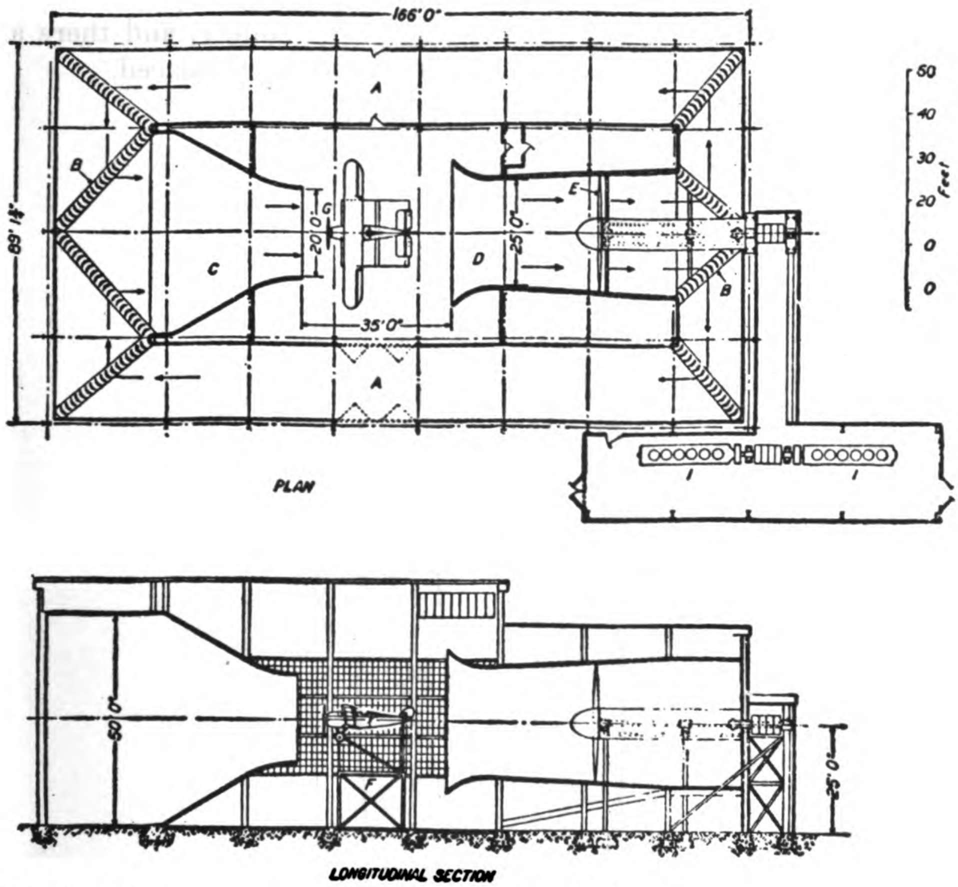
(*d*) An experimental chamber or throat fitted to hold the object to be tested in the desired attitude.

(*e*) A system of linkages for transmitting the forces to measuring balances.

(2) There are three general types of wind tunnel. Both of the types in (*a*) and (*b*) below may have a return channel for the air

discharged, for the power required to maintain the proper velocity of airflow is thus reduced.

(*a*) *Closed chamber type.*—The experiment chamber is closed and the balances are outside the tunnel. The model is visible through a glass pane in the chamber. The diagram in figure 27 illustrates the type.



A. Return passage
B. Guide vanes
C. Entrance cone
D. Exit cone
E. Circulating fan
F. Balance
G. Test propeller

Open throat; return flow; 2,000 hp.; 110–115 m. p. h.

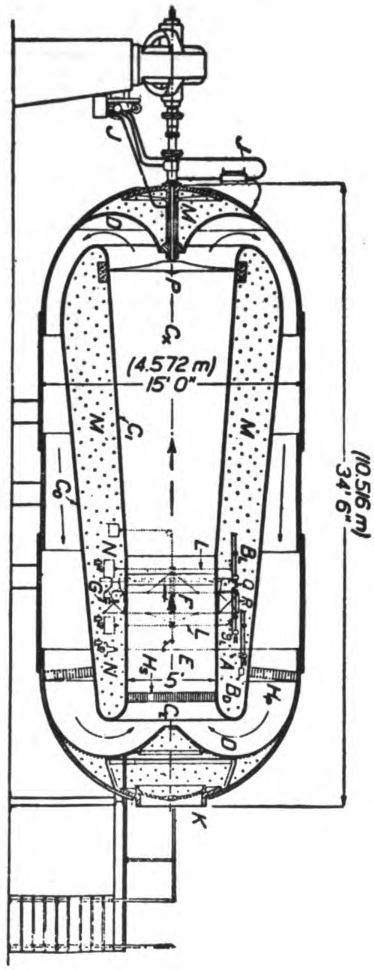
FIGURE 28.—N. A. C. A. 20-foot propeller research tunnel.

(*b*) *Open chamber type.*—For the testing of full scale objects such as propellers, fuselages, etc., it is often essential to break the wind tunnel at the throat and place the body to be tested in this opening between the inlet and outlet cones.

(*c*) *Variable density type.*—This is a tunnel of the closed chamber, closed return type, differing therefrom in that the air in circulation can be compressed to over 20 atmospheres. Such compression is

desirable to maintain dynamic similitude between the action of the air on the model and on the full scale object, thus eliminating the "scale effect".

The larger the wind tunnel the larger the object which can be tested and consequently the more accurate will be the results in the case of a model since its scale more closely approaches that of actual conditions. The size of the tunnel, however, is limited by the cost. A small one would have a 3-foot experimental chamber, and there are several now in use in which an entire airplane can be placed.



A. Amplifying indicator	D. Deflector	K. Door
B_L. Lift balance	E. Experiment chamber	L. Vertical rod
B_D. Drag balance	F. Model	M. Dead-air space
C_E. Entrance cone	G. Angle of attack mechanism	N. Weight
C_X. Exit cone	H_P. Primary ring honeycomb	P. Propeller, 2-blade, 7 ft.
C_O. Outer cone	H_S. Secondary honeycomb	Q. Revolution counter
C_I. Inner cone	J. Oil-seal mechanism	R. Balance ring

FIGURE 29.—Longitudinal section of N. A. C. A. variable density wind tunnel, Langley Field, Va.

c. Balances.—(1) The balances used for the measurement of forces acting on a model in a wind tunnel are of several types. One type is shown in figure 30.

(*a*) The model is mounted on a spindle which is attached to the balance. The whole apparatus is supported on a hardened steel or

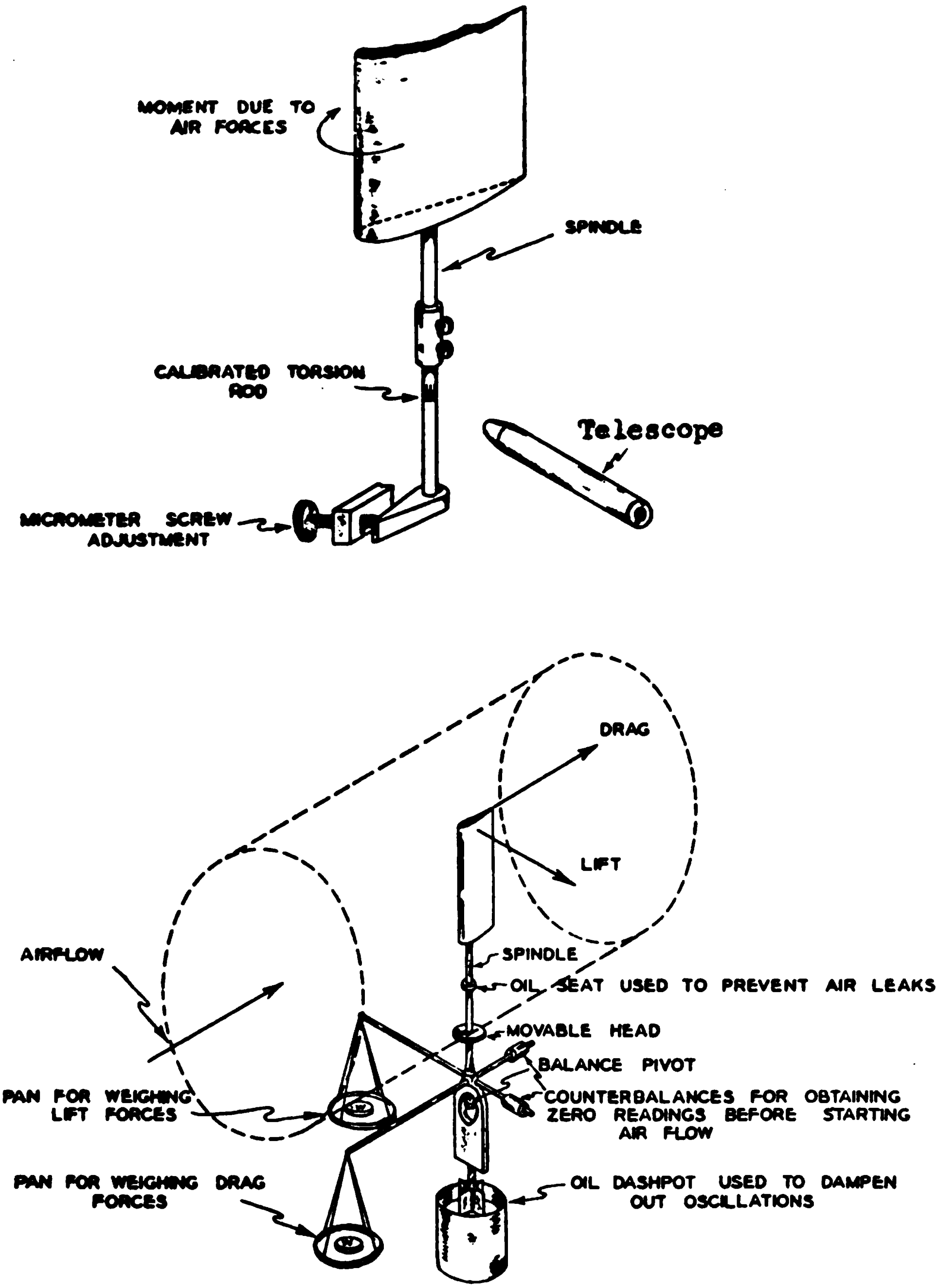


FIGURE 30.—Wind tunnel balance, N. P. L. type.

jeweled point. The model is mounted vertically, since as far as the air forces are concerned it makes no difference whether the lift is measured vertically or horizontally.

(*b*) The drag acts horizontally in any case. When the set up is made, the whole apparatus is balanced with the counterweights before air is drawn through. It will be seen that the lift and drag arms of the balance, equipped with scale pans, can be made to balance the lift and drag forces and thus measure them directly. The model is attached to a spindle which is in turn mounted on a movable plate. This plate is calibrated in degrees and by turning it, the angle of the model to the wind can be accurately set without touching the model.

(*c*) Figure 30 shows the apparatus for measuring moments. In this case the spindle is rigidly attached to a torsion rod, which has been calibrated so that a known number of turns of the micrometer screw is equivalent to a known number of inch-pounds. When the model is set up the reference line on the torsion rod is brought into line with the cross hair in the microscope. When the wind is turned on, the air forces cause a certain moment on the airfoil, in turn causing a rotational movement in the torsion rod.

(*d*) To measure the moment, the micrometer screw is rotated until the reference line is brought back into coincidence. Reference to a torsion curve will give the moment. Some balances have a third weight pan to bring the torsion rod back to its original position, but the principle is the same.

(2) Figure 32 shows a typical "wire type" balance which is used for large models and high throat velocities. The airfoil is mounted upside down. It will be seen from the figure that the pull in the two drag wires *a* is exactly equal to the drag through the action of the wires running to the floor at an angle of 45°. The two lift wires *b* carry part of the lift; the remainder is carried through a single wire *c* which is attached to a "sting" or spindle extending out from the trailing edge of the airfoil. The center of pressure can be determined without any other measurements being made. Take the moment of the load in wire *c* about the leading edge, the distance between the wires *b* and *c* being accurately known, and divide this moment by the sum of the loads in wires *b* and *c*.

d. Uses.—(1) Most of the laws of aerodynamics and all of the formulas have been developed or checked through wind tunnel experiments. In no other manner can conditions simulating flight be obtained, and even in flight it would be very expensive or almost impossible to make observations of certain of the forces and airflows existing. The wind tunnel, then, is of incalculable value in aero-

dynamic research. Among the qualitative and quantitative results to be expected with adequate engineering accuracy from the tunnel are—

(*a*) The resistance offered by any sort of object to an airstream.

(*b*) The comparative value of various types of fairings and stream lining.

(*c*) The lift and drag of airfoils.

(*d*) The efficiencies of all types of propellers.

(*e*) The effectiveness of new "gadgets", such as slotted wings, etc.

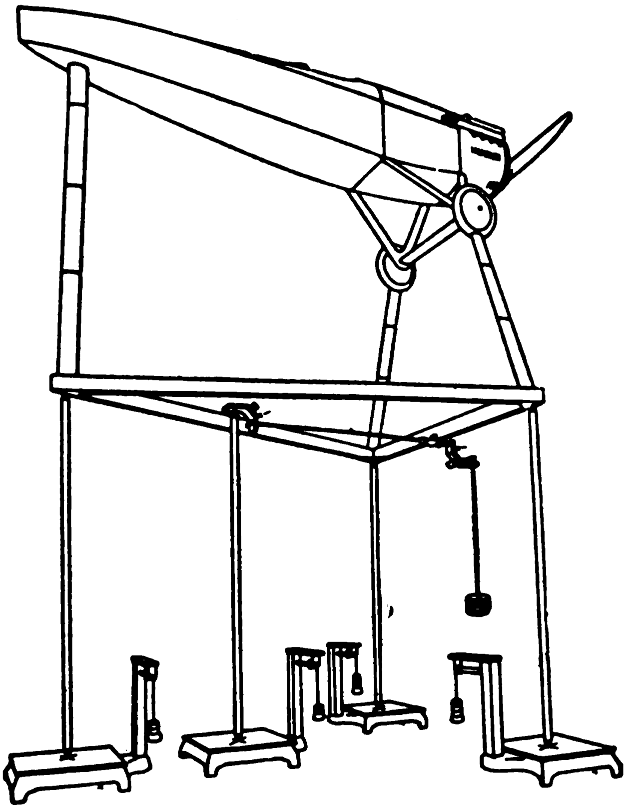


FIGURE 31.—Special balance for N. A. C. A. 20-foot propeller research tunnel.

(*f*) The air resistance of vessels.

(2) One of the most important uses of the wind tunnel is that of testing complete models. The purpose of these tests is to check the predicted performance, stability, and control of the airplane as laid out on paper prior to undertaking actual construction of the machine or even the detail design of parts and assemblies. The advantages accruing include savings in time, labor, and cost, for quick and definite indications are assured as to the adequacy of the design or the need for modifications.

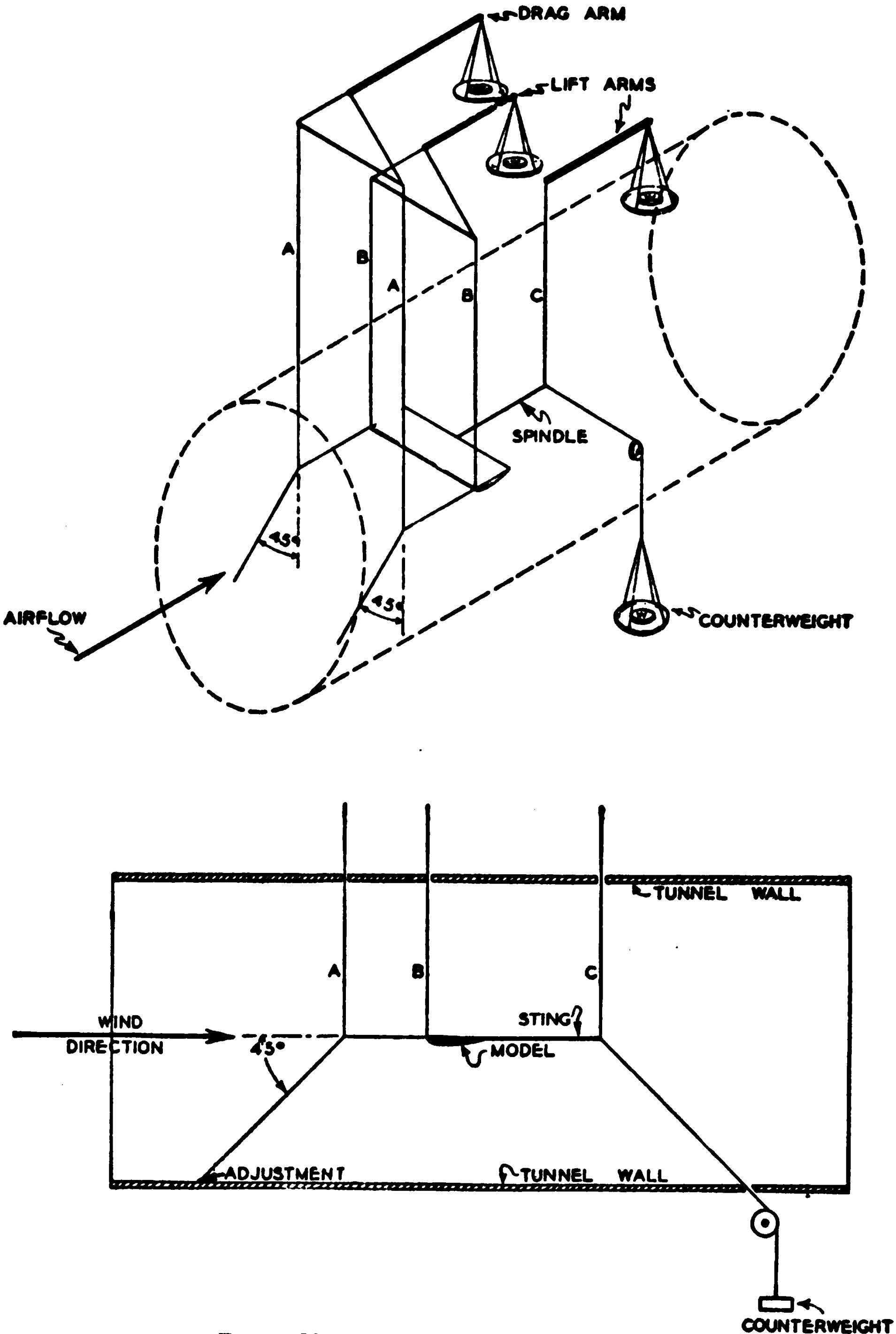


FIGURE 32.—Wind tunnel balance, wire type.

Section III

AIRFOILS

35. Airfoil characteristics.—A particular airfoil, that is, one of specific dimensions, is characterized by the following properties:

a. Lift coefficient.

b. Drag coefficient.

c. Lift-drag ratio.

d. Center of pressure position.

In lieu of center of pressure position some equivalent property may be used, such as the moment of aerodynamic force about the leading edge. These quantities are collectively known as airfoil "characteristics".

36. Lift coefficient.—*a.* For any angle of attack the lift coefficient value of an airfoil is obtained from the fundamental equation of lift—

$$L = C_L \rho/2 S V^2 \tag{24}$$

Since the lift must equal the weight of the airplane to satisfy conditions of equilibrium in unaccelerated or steady flight—

$$C_L = \frac{W}{\rho/2 S V^2} \tag{25}$$

Both the weight of a given airplane and the area of its wings are constant quantities.
The air density ρ varies with the altitude. Assuming the flight to occur at a constant value of ρ, it is evident that the lift coefficient varies inversely with the airspeed, or

$$C_L \sim \frac{1}{V^2} \tag{26}$$

b. For a particular airplane, it is possible to spot in airspeeds for corresponding lift coefficients and angles of attack as illustrated in figure 34. This shows conclusively that *for unaccelerated flight there is one airspeed and only one for a given angle of attack and vice versa.*

c. The curve, it will be noted, is practically a straight line throughout the flight range. It crosses the zero ordinate at a small negative angle of attack which represents the vertical dive attitude. As it approaches its maximum value the slope changes rapidly indicating that with speed variations near the stall, relatively large changes in angle of attack are necessary to maintain the requisite lift. This flattening of the curve with increase in angle of attack is due to turbulence which eventually becomes so pronounced as to bring about an actual reduction in lift coefficient.

(1) These characteristics will vary with change in angle of attack of the airfoil since they depend on forces which vary in this manner. It is, therefore, convenient to plot them to definite scale against angle of attack. The resulting curves are termed the "characteristic curves" of the airfoil and are illustrated in figure 33 by a typical example.

(2) Results of wind tunnel tests on a large number of airfoils show that while the characteristic curves vary for the different shapes, they follow, in general, the same trend with corresponding values differing only in degree.

(3) The effect of turbulence is illustrated in figure 35.

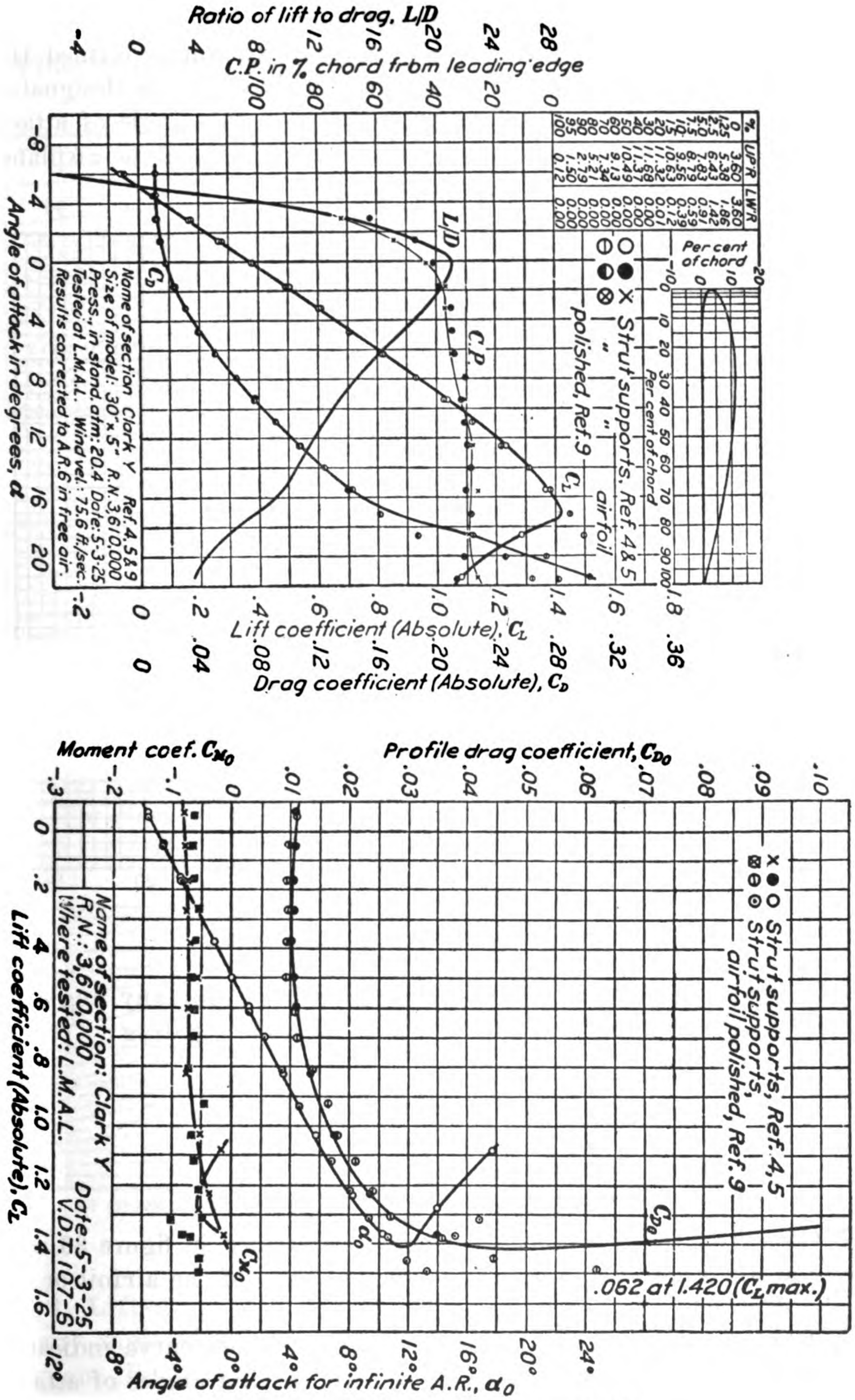


FIGURE 33.—Clark Y airfoil characteristics.

d. The lift coefficient attains a maximum value at an angle of attack in the neighborhood of 15°. This maximum is termed the "burble point." The angle of attack for maximum C_L is designated as the "critical" or "stalling" angle since above this angle of attack the lift afforded is insufficient to support the weight of the airplane.

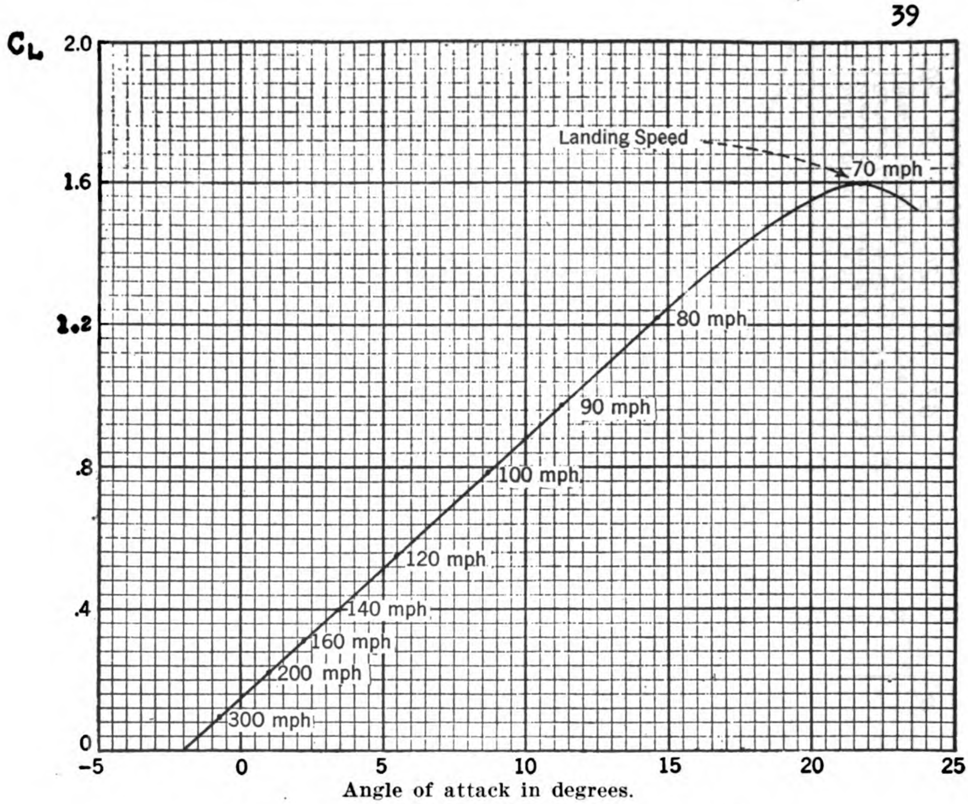


FIGURE 34.—Full-scale airplane characteristics.

37. Drag coefficient.—*a.* The drag coefficient for any angle of attack is obtained from the fundamental formula for drag:

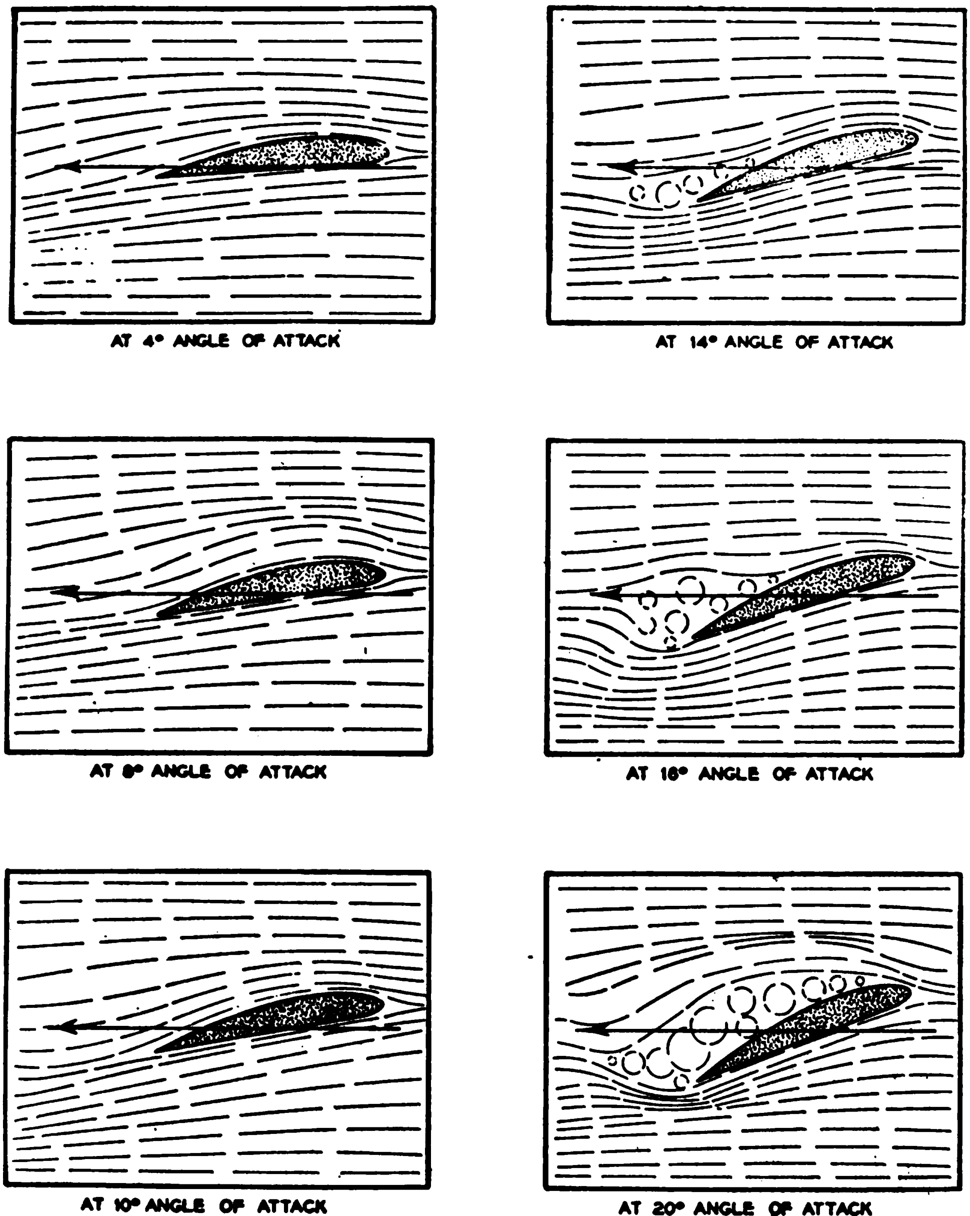
$$D = C_D \frac{\rho}{2} S V^2$$

$$\text{or } C_D = \frac{D}{\rho/2 S V^2} \tag{27}$$

b. Obviously the drag coefficient curve illustrated in figure 36 will never attain a zero value regardless of the shape of the airfoil or its angle of attack.

c. It must be remembered that the drag coefficient curve indicates the variation of the airfoil drag alone with varying angles of attack and does not take into account the resistance offered by the remainder

of the airplane. While a similar condition exists with regard to the lift coefficient, the remainder of the airplane contributes so little to the lift that no account is taken of it.



Angle of attack in degrees.

FIGURE 35.—Airflow past airfoil.

38. Lift-drag ratio.—The ratio of the lift to the drag of an airfoil at any angle of attack is a measure of its "effectiveness," for, in the airplane the former is the useful force, or the one required to support the weight while the latter is the unbeneficial one which must be

accepted to obtain sustentation. This ratio, termed the L/D ratio, will vary considerably with angle of attack as shown in the curve of figure 37. The curve is determined by plotting against angle of attack lift values divided by corresponding drags or it may be derived from the curves of C_L and C_D. For any angle of attack the C_L value divided by the C_D value will give the L/D for that angle. That this is correct can be shown by dividing the equation for lift by that for drag:

$$\frac{C_L\rho/2SV^2}{C_D\rho/2SV^2} \tag{28}$$

Since $\rho/2$, S, and V are common:

$$\frac{L}{D}=\frac{C_L}{C_D} \tag{29}$$

From a zero value for the angle of attack of zero lift, the curve rises to a maximum at an angle of attack ranging ordinarily from 1° to 4°. Thereafter it falls off more gradually and in a variety of ways for different airfoils.

While the maximum value of L/D for the airfoil is in the neighborhood of 20, that for the complete airplane is somewhat less than half this value. This is due to the fact that for the airplane—

$$\frac{L}{D}=\frac{\text{Lift}}{\text{wing drag}+\text{parasite drag}} \tag{30}$$

The parasite drag, or drag of the airplane exclusive of the wings, varies comparatively little with change in angle of attack. Hence the L/D curve, besides having much lower values, will have a flatter peak with maximum probably somewhat shifted as shown in figure 37. The angle of attack for this maximum value will be that for the best glide without power as will be demonstrated.

For the wings alone, it is obvious that, other things being equal, the airfoil having the best maximum L/D will be the most acceptable.

39. Center of pressure.—Bearing in mind the variation in pressure distribution along the chord with change in angle of attack, the point of application of the resultant, that is, the center of pressure, shifts correspondingly. Throughout most of the flight range, there is a backward movement of the center of pressure with decrease in angle of attack as evidenced in figure 38. The most forward position is generally about 0.3 of the chord abaft the leading edge and obtains, as a rule, somewhat below the "critical" angle. The backward shift from this position becomes abrupt as low angles are reached and the center

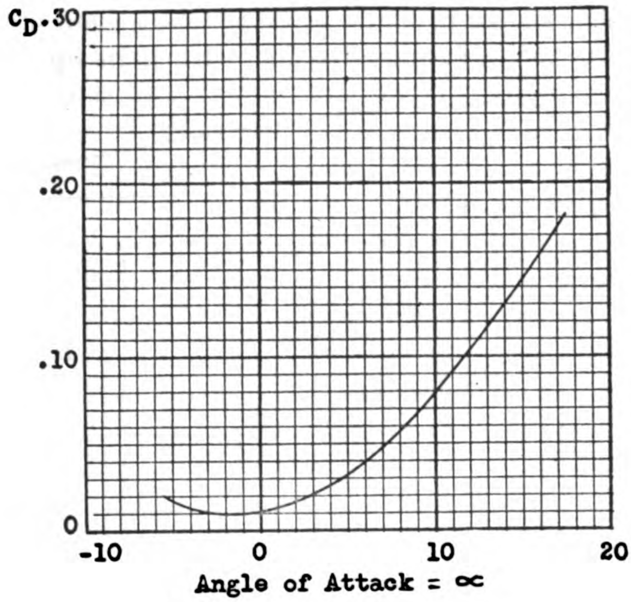


FIGURE 36.—Variation of C_D.

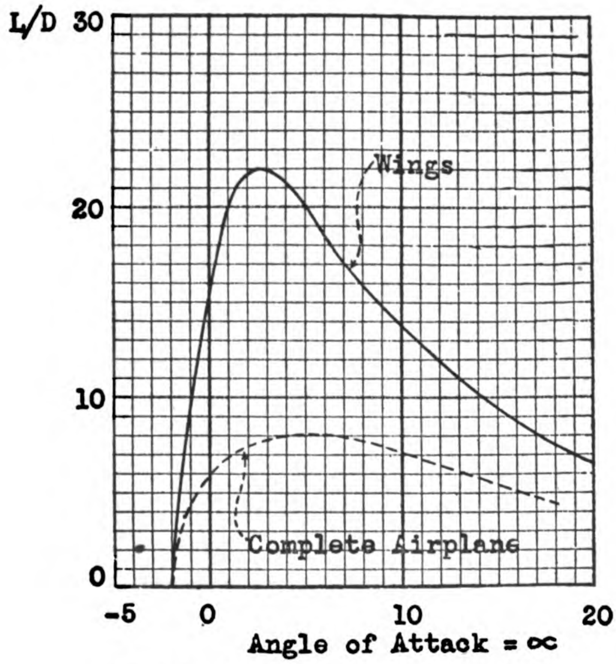


FIGURE 37.—Variation of L/D ratio.

of pressure finally runs off the trailing edge, approaching infinity for the angle of attack of zero lift. This travel of the center of pressure on an airfoil is said to be unstable for, with it in equilibrium at any

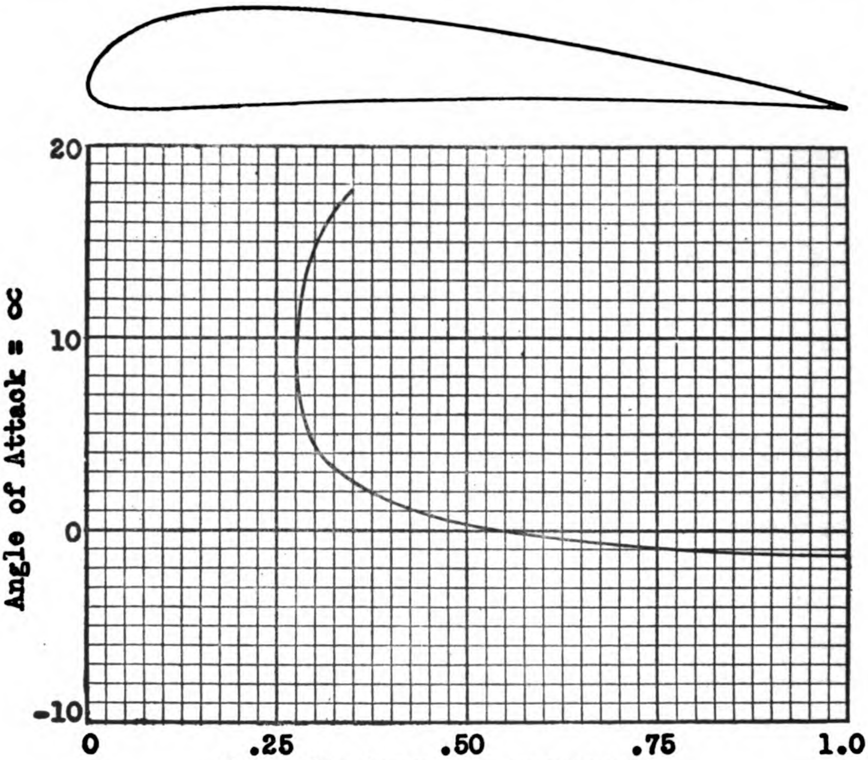


FIGURE 38.—Center of pressure travel.

angle of attack, a disturbance will produce a moment which will augment the effect of such a disturbance rather than one which will tend to restore the airfoil to its previous attitude once the disturbance sub-

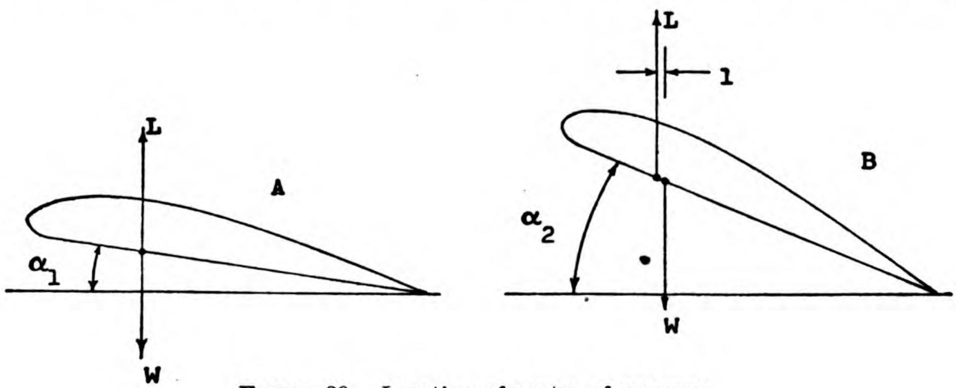


FIGURE 39.—Location of center of pressure.

sides. This is illustrated in figure 39. In *A* the airfoil is at an angle of attack α_1, and in equilibrium with respect to the vertical forces for $L=W$ and there is no moment of lift. An upgust forces the airfoil to

a new angle of attack α_2 as shown in *B*. The lift must move forward but the weight will remain at the assumed center of gravity. A clockwise moment $L \times 1$ is thus exerted tending further to stall the airfoil. This unstable travel of the center of pressure is characteristic of practically all airfoils employed. Without horizontal tail surfaces, a primary function of which is to impose counteracting moments, no conventional airplane would long remain in flight.

40. Airfoil dimensions.—The characteristics of an airfoil are influenced by the proportions of the plan view and by the amount of curvature of the section. The plan form of an airfoil is characterized by its span, chord length, aspect ratio, and contour of the wing tips.

a. Span is defined as being the distance between the wing tips, including ailerons.

b. The chord is the line of a straight edge brought in contact with the lower surface at two points or, in the case of an airfoil having double convex curvature, the line between the leading and trailing edges. (For the double convex section the edges may be defined as being the two points in the section that are farthest apart.) The method used in determining the chord must be stated in cases where ambiguity might exist.

41. Camber.—This quantity is the convexity or rise of an airfoil section above the chord. At any point the camber is expressed as a percentage of chord length and is a distance perpendicular to it. The coordinates and scheme of designating the section are shown in figure 40. The chord length is either the length of the straight line drawn between the leading and trailing edges as in *A* or is the distance between perpendiculars dropped from the leading and trailing edges to the chord as in *B*. The abscissa of any point is designated in percentage of the chord length, x/c, using the intersection of the chord with the leading edge as origin. The camber is the ordinate expressed in percentage of the chord as a/c and b/c.

42. Airfoil profiles.—*a.* Airfoil profiles may be considered as made up of a certain profile thickness form disposed about a mean line. The major shape variables then become two, the thickness form and the mean line form. The thickness form is of particular importance from a structural standpoint. On the other hand, the form of the mean line determines almost independently some of the most important aerodynamic properties of the airfoil section, e. g., the angle of zero lift and the center of pressure travel.

b. In wide use today are airfoil profiles developed as the result of systematic investigation by the N. A. C. A. The airfoils of this series are designated by a number of four digits; the first indicates the camber of the mean line in percent of the chord, the second the

position of the maximum camber of the mean line in tenths of the chord from the leading edge; and the last two, the maximum thickness in percent of the chord. Thus N. A. C. A. 2215 airfoil has a maximum camber of the mean line of 2 percent of the chord at a position 0.2*c* from the leading edge, and a maximum thickness of 15 percent of the chord.

c. An additional family of profile shapes developed about a mean line of different camber distribution has been tested by the N. A. C. A. Some of these profiles have excellent aerodynamic characteristics and find favor with designers. The profiles of this series are designated by a number of five digits. Thus N. A. C. A. 22015 airfoil has a maximum camber of the mean line of 2 percent of the chord at a position 0.2*c* from the leading edge; a maximum thickness of 15 percent of the chord; and the shape of the curve of the mean line is from a family designated by the digit 0.

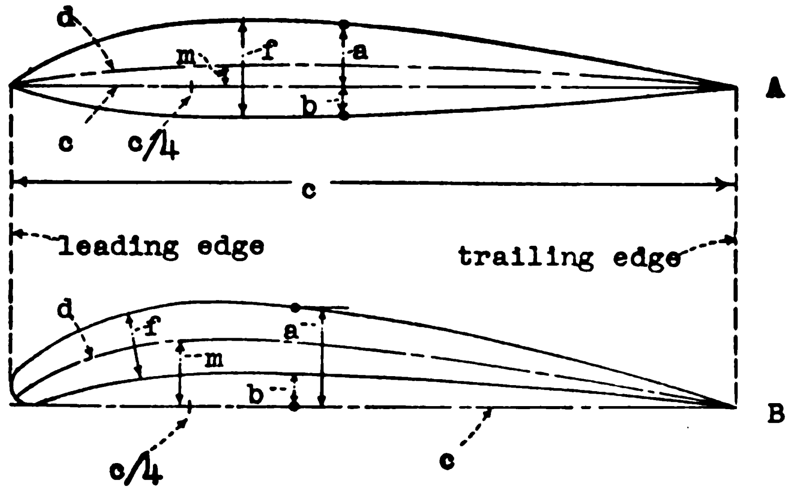
d. Different types of airplanes require widely varying wing sections. An airplane whose sole purpose is the transportation of heavy loads for relatively short distances may employ a wing section to give maximum lift without much consideration for drag. A racing airplane, on the other hand, may employ a thin section to permit a low resistance. The military airplane should have the weight-carrying capacity of a condor, the speed of a blue goose, and the maneuverability of a bat. It is necessary for the designer to sacrifice some of the desired characteristics and select a wing section that will satisfy the most important conditions.

43. Aspect ratio.—*a.* The span of an airfoil is the maximum transverse dimension normal to the relative wind, or the distance between the wing tips. The span therefore determines the amount of air acted upon and hence is an important factor in the production of lift by a given wing area. For an airfoil of rectangular plan form the ratio of span to chord is termed "aspect ratio." Thus an airfoil having a span of 30 feet and a chord of 6 feet would have an aspect ratio of 5. Very seldom however is an airfoil rectangular in plan form due to the employment of tapered wings, center section cut-outs, and various tip shapes. Consequently the aspect ratio is defined as span squared divided by area or—

$$\text{Aspect ratio} = b^2/S$$

b. The influence of aspect ratio on the airfoil and its characteristics hinges on the variations in airflow and pressure distribution with change in plan form. Were the airfoil of infinite span the airflow would be direct from leading to trailing edge for there would be no

way for the streamlines below the surface to flow from this area of relatively high pressure to that of reduced pressure above. Since the airfoil is of finite area and span, air on the under side will seek the low pressure region above by "spilling" over the tips. Vortices or



a/c. Upper camber.
b/c. Lower camber.
m/c. Mean camber.
c. Chord length.
d. Mean line of airfoil profile.
c/4. Aerodynamic center (quarter-chord point).
f. Profile thickness.

FIGURE 40.—Method of defining airfoil profile.

eddies are thus formed at the tips, and the streamlines above and below the airfoil are deflected transversely as shown in figure 42.

The streamlines on the under side bend toward the tips, while those above bend toward the center owing to the pressure gradient produced. The "tip vortex" increases the drag on account of the turbulence created which absorbs energy. They, furthermore, cut down the lift by destroying the section forces of the airstream above the airfoil close to the tips. Since these eddies are unavoidable, the only recourse is to reduce their effect as much as possible. This is accomplished by increase in aspect ratio. For a given airfoil area the tip

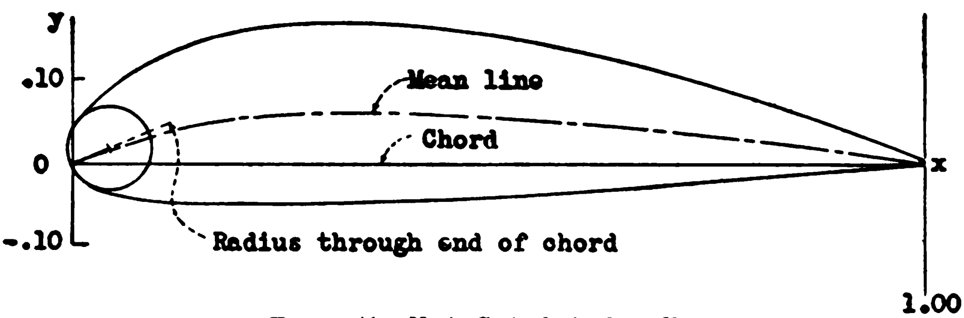


FIGURE 41.—N. A. C. A. derived profile.

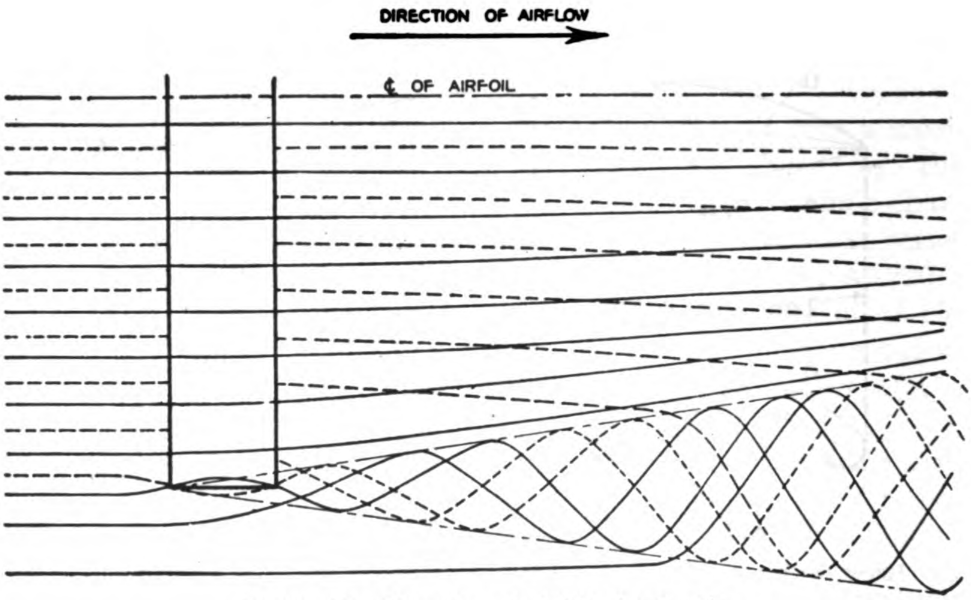


FIGURE 42.—Plan view of airfoil at wing tip.

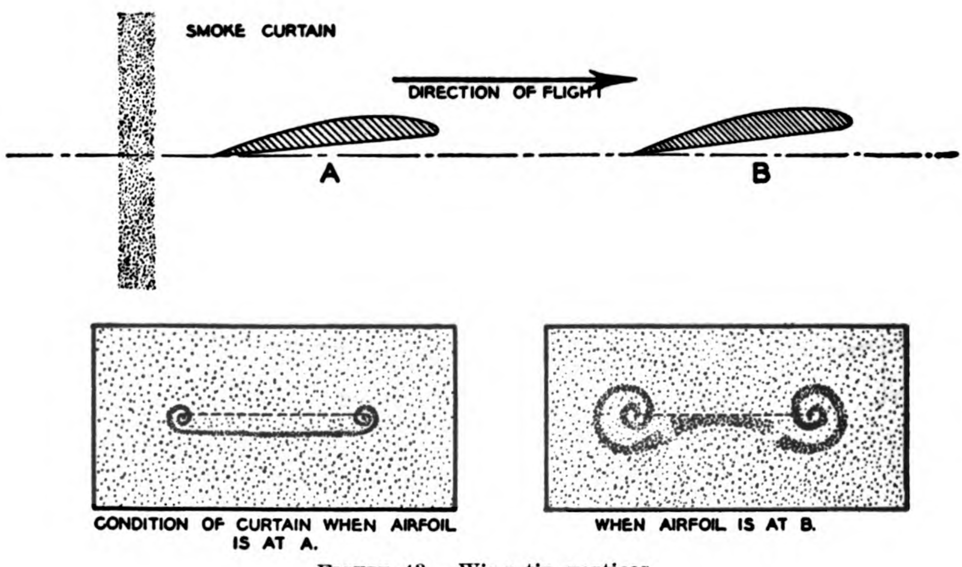


FIGURE 43.—Wing tip vortices.

vortices will be felt for an appreciable distance in from the tips. In figure 44 this distance is represented by x. The airfoil area is the same in each case. In *A* the area suffering from tip losses is $2cx$ and is much greater than in *B* where the value of c_2 is smaller and very much greater than in *C* where c^3 is still less.

c. Besides reducing the effect of tip vortices, increase in aspect ratio is directly beneficial to lift. This is due to the fact that the greater the aspect ratio the greater the mass of air to be given a downward momentum. Hence the lift coefficient will be greater, or for a given lift the amount of downward deflection can be reduced, thus lowering the drag.

d. To summarize, the airfoil characteristics are influenced as follows by increase in aspect ratio:

(1) The maximum value of C_L is increased.

(2) C_D values will be lower throughout the flight range. This is most marked at high angles of attack.

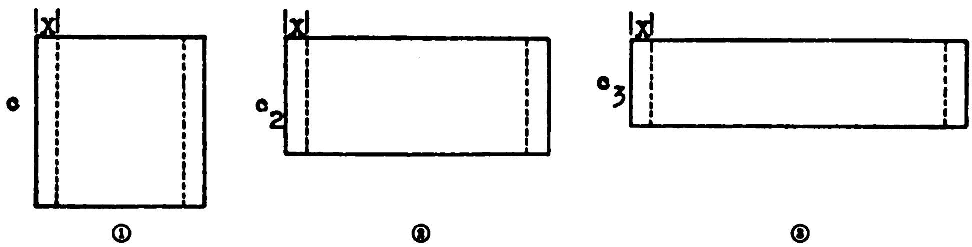


FIGURE 44.—Area effected by tip vortices.

(3) The *L/D* is increased, with values particularly improved at high angles of attack.

e. From the foregoing it would appear that as high an aspect ratio as possible would give the most efficient airfoil. There are limitations in high aspect ratio in that too long a wing will require a larger amount of external bracing causing an increased drag and embracing more weight. In the case of the cantilever wing the root section must be of heavy construction and the necessity for increased material may offset the gain in lift. For these reasons aspect ratios have an upper limit of about 10 at the present. Improvements in metals may permit longer wings in the future. With increased aspect ratio the slope of the lift curve is steeper, indicating greater changes of lift with change in angle of attack and that the burble point is reached somewhat sooner.

f. It is interesting to note that some American racing airplanes and and fast low wing fighting airplanes employ a relatively low aspect ratio (5). This permits better control in landing, for the stall is less

abrupt and the drag is not much affected by a low aspect ratio at low angles of attack.

44. Induced drag.—*a.* By application of hydrodynamic theory, the following equation for induced drag has been derived:

$$\text{Induced drag} = \frac{C_L \times \text{Lift}}{\pi \times AR} \tag{31}$$

$$C_{Di} = \frac{C^2_L}{\pi AR} \tag{32}$$

$$C_D = C_{Di} + C_{Do} \tag{33}$$

where C_{Di} is the coefficient of induced drag and C_{Do} is the coefficient of profile drag.

b. The relationship between lift, profile drag, and induced drag is shown in figure 45. This curve is a "polar curve". It will be observed that—

(1) When the lift is zero the induced drag is zero.

(2) At small angles of attack the induced drag is small in comparison to the profile drag.

(3) At large angles of attack the induced drag is large in comparison to the profile drag.

(4) The profile drag coefficient is nearly constant throughout most of the flight range.

c. Another method of plotting the aerodynamic characteristics of an airfoil is becoming widely used. (Fig. 46.) In this method, C_{Do} is plotted against C_L and C_{Di} is computed. The total drag coefficient is therefore—

$$C_D = C_{Do} + \frac{C^2_L}{\pi AR} \tag{34}$$

The angle of attack for infinite aspect ratio α_0 is also plotted against C_L, and the angle of attack α for any particular wing computed as follows:

$$\alpha = \alpha_0 + \frac{18.24\, C_L}{AR} \tag{35}$$

45. Taper.—*a.* An airfoil is said to be tapered when a gradual decrease has been given to one or more of its dimensions in progressing from the plane of symmetry, or centerline, to the tip. The airfoil section at the centerline or, as in the case of a lower wing, at the fuselage is called the "root" section; that at the tip, the "tip" section. By maintaining the chord length constant and decreasing the camber, taper in thickness is obtained. By maintaining the camber constant

and reducing the chord length, taper in plan form is produced. It is usual to employ taper in both plan form and thickness if employed at all.

b. Tapering a wing presents certain aerodynamic advantages. These advantages are offset by the fact that the tapered wing presents structural difficulties. The spars must be tapered and all ribs must be built in different jigs. Both these considerations increase

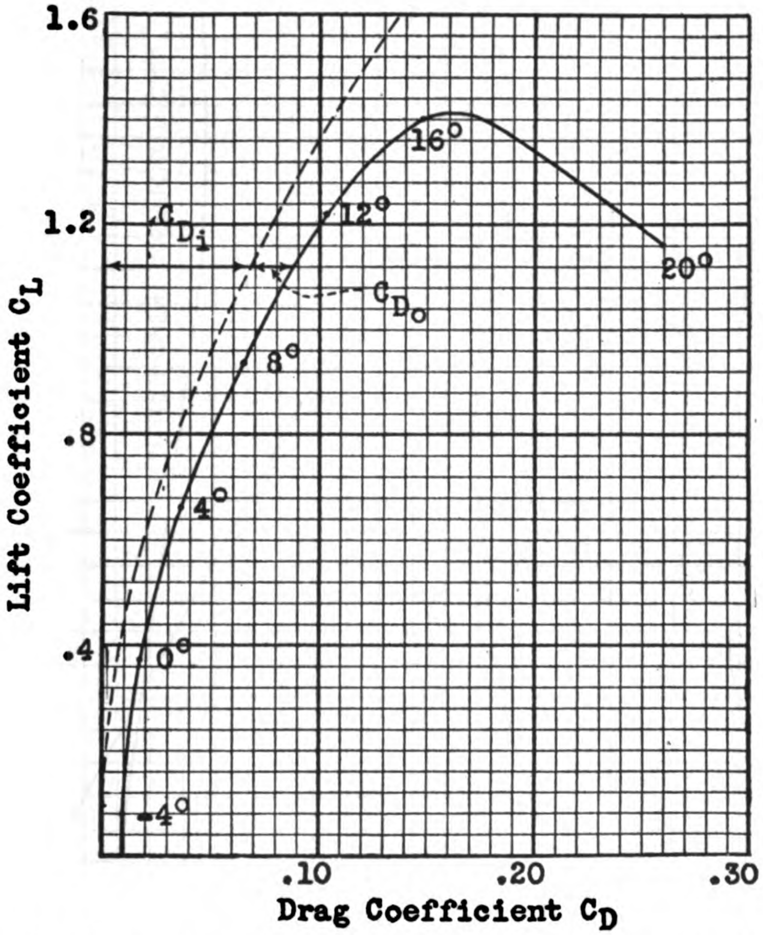


FIGURE 45.—Polar curve for Clark Y airfoil, aspect ratio 6 RN 3,610,000.

the cost of production and the designer must exercise judgment as to whether the aerodynamic advantages justify the increased cost.

c. The distribution of area is such that the resultant force is relatively close to the center line and hence a lighter structure is permissible. Furthermore, flight tests have shown tapered wings to be more easily controlled in flight by proper arrangement of angles of incidence along the span.

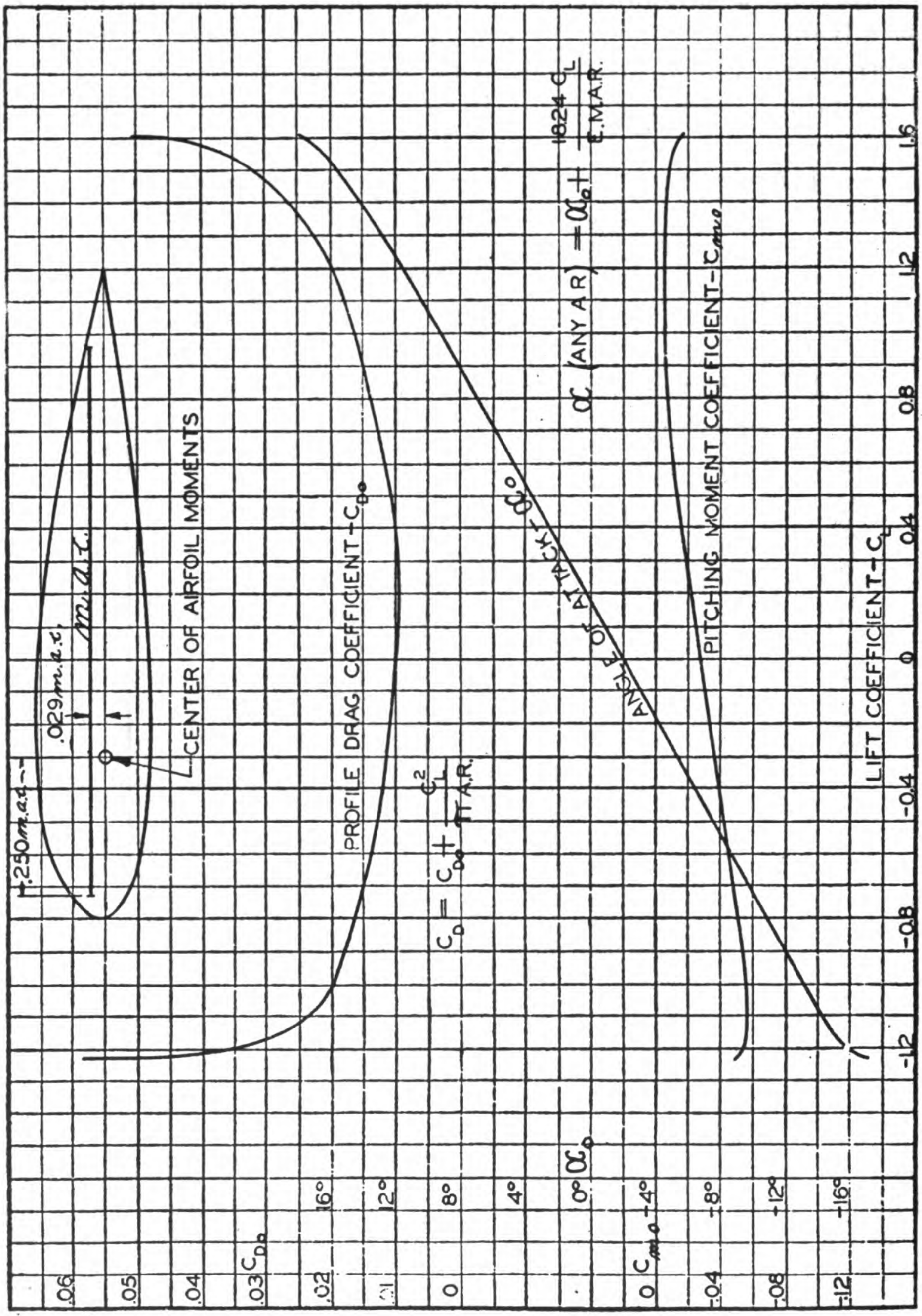


FIGURE 46.—Aerodynamic characteristics of N. A. C. A. 2218–09 tapered airfoil.

d. As compared with a rectangular airfoil of equivalent aspect ratio, a pronounced taper in plan form influences the airfoil characteristics as follows:

(1) Higher maximum C_L results.

(2) Lower values of C_D obtain, especially at low angles of attack.

(3) L/D is higher throughout the flight range, and especially so at high angles of attack.

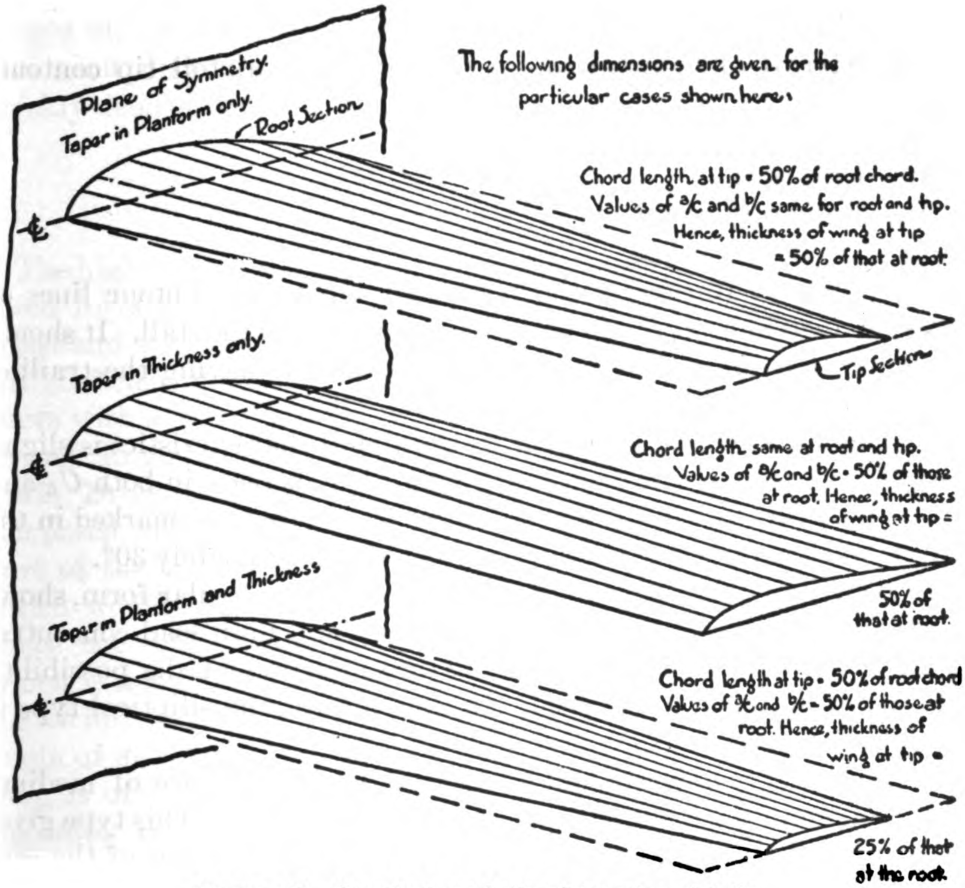


FIGURE 47.—Standard methods of tapering airfoils.

(4) A somewhat greater movement of the center of pressure results with change in angle of attack.

e. Pronounced taper in thickness, say with the tip 60 percent that of the root, gives the following results in comparison with an airfoil of constant section equal to the average or mean section of the tapered wing:

(1) The maximum C_L is greater with the peak of the characteristic curve flattened since the various sections attain their maxima at different angles of attack.

(2) The C_D values are lower with the most pronounced decrease at small angles of attack.

(3) The maximum L/D is higher and values of L/D at small angles of attack are larger.

(4) The center of pressure movement is somewhat less for changes in angle of attack.

f. A proper employment of taper both in plan form and thickness will give an airfoil having characteristics which take advantage of the benefits of each kind.

46. Airfoil tip contours.—*a.* The types of airfoil tip contours are—

(1) Rectangular.
(2) Elliptical.
(3) Positively raked.
(4) Negatively raked.

b. Figure 48 illustrates the types and shows the contour lines of pressure distribution for an angle of attack close to the stall. It should be noted that the positively raked tip is the one having the trailing edge longer than the leading edge.

c. The influence of tip contour on the airfoil characteristics is slight, any change from the rectangular giving some increase in both C_L and L/D and a decrease in C_D. The improvements are most marked in the elliptical tip and that with negative rake of approximately 30°.

d. The tip with positive rake, as also that of rectangular form, shows a relatively uneven distribution of pressure and high load concentration. These dictate a stronger structure and present the possibility of aileron flutter at high speed. In consequence, the elliptical type is usually favored.

e. The most commonly employed airfoils of today are of medium thickness employing negative or convex lower camber. This type gives a good lift-drag ratio, low resistance, and slight movement of the center of pressure. It also permits relatively high speeds with the available horsepower and wings thick enough for an efficient structure.

47. Airfoil selection.—In the selection of the proper airfoil for a particular airplane type, the factors to be considered will in many cases conflict, necessitating compromises. Principal among these factors are—

a. Airfoil characteristics.
b. Airfoil dimensions.
c. Stability of airflow about the airfoil.
d. Adaptability of the airfoil to construction.
e. Operating limitations.

With very complete data available on hundreds of airfoils it would appear to be a hopeless task to select any particular one for a given purpose. However, whole groups of airfoils can be almost immediately discarded as evidencing undesirable qualities. Further analysis then quickly narrows the field to a very few acceptable shapes.

48. Lift coefficient criteria.—An airplane should have as low a landing speed as possible. For a given "wing loading" this is fixed by the maximum lift coefficient. Wing loading is the ratio of the weight of the airplane in pounds to the wing area in square feet and varies but slightly for a particular type. The landing speed is then quickly determined from the formula—

$$V_{min}=\sqrt{\frac{W}{\rho/2SC_{L max}}} \tag{36}$$

The higher the maximum lift coefficient the lower will be the landing speed for a given wing loading. If, on the other hand, the landing speed and weight are fixed by specifications, the higher the maximum lift coefficient the smaller the necessary wing area. A lift coefficient curve with a sharp peak or an unstable region at $C_{L\ max}$ is undesirable as such an airfoil contributes to loss of control at stalling speeds.

49. Drag coefficient criteria.—The total drag on an airfoil is composed of induced drag and profile drag. Induced drag is that part of the total which results from deflection of the airstream and which would be the total drag were the air a nonviscous fluid and hence not subject to eddies. Profile drag is that part of the total which is due to skin friction and turbulence. It will vary only with the airfoil section employed, whereas the induced drag will vary with angle of attack and the aspect ratio of the airfoil. A low minimum drag is of vital importance to high speed airplanes, and in general the lower the minimum drag coefficient the greater is apt to be the high speed attainable.

50. L/D ratio criteria.—To determine the wing drag of an airplane of given weight at any angle of attack it is only necessary to divide the weight by the L/D ratio for that angle, or

$$D=\frac{W}{L/D} \tag{37}$$

This is obvious from the condition that the lift must equal the weight in steady flight. For a given weight, then, the greater the L/D ratio the smaller the drag at the particular angle of attack. While a good L/D ratio is desirable in the racer, minimum drag is of paramount importance. Where good climb and long range are the

controlling factors, a high L/D ratio is essential owing to the economy afforded. This is due to the relatively low thrust required which in turn permits lower engine power and so a smaller fuel consumption.

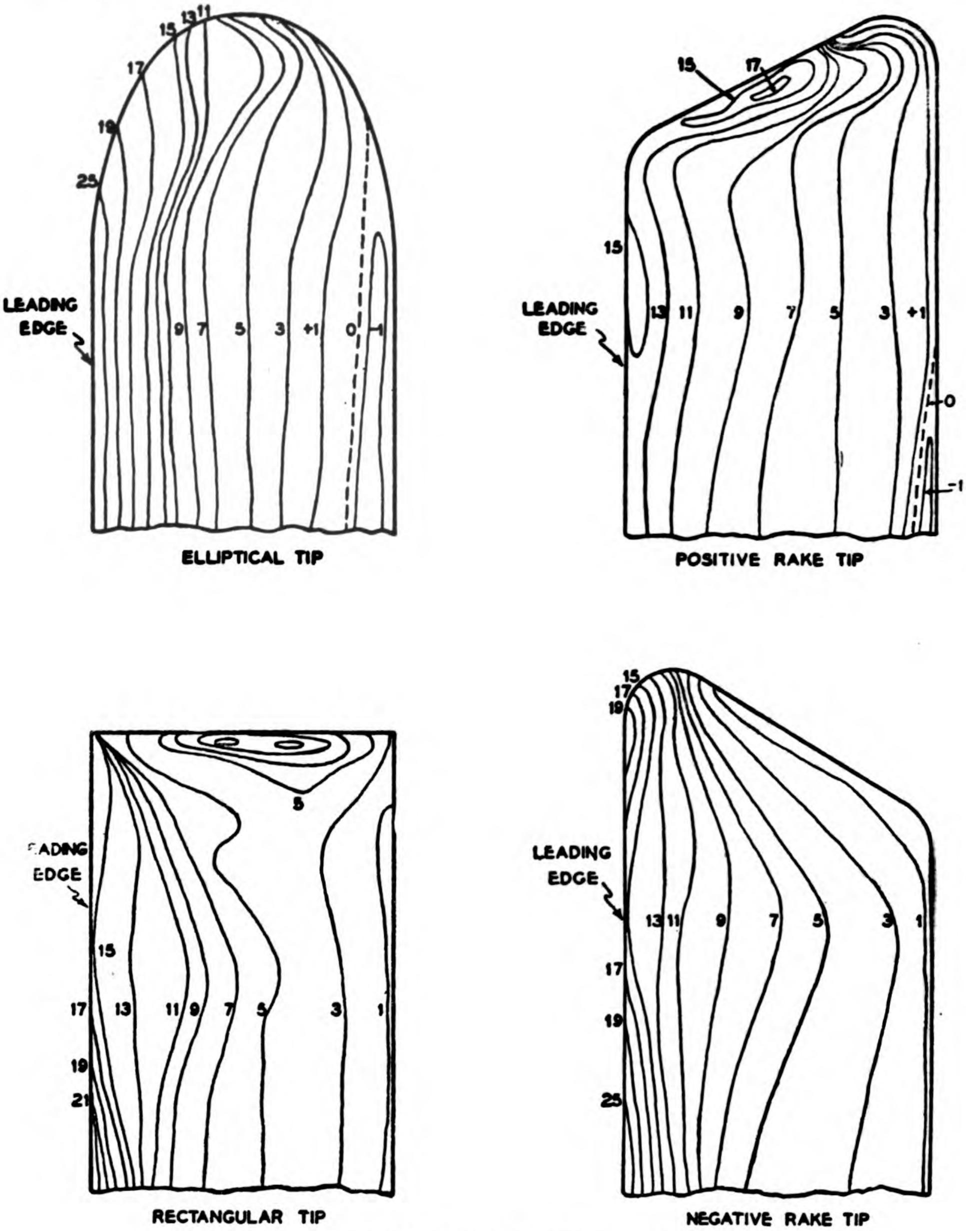


FIGURE 48.—Pressure distribution on airfoil tips.

51. Center of pressure criteria.—The distribution of load between the front and rear spars of an airplane wing as also that in its lift truss varies with movement of the center of pressure. Consequently the members must be built to withstand the worst loads to

which they are subjected, which are bound to be greater than if the center of pressure were stationary. Other things being equal, then, the airfoil exhibiting the smallest center of pressure travel will be the lightest for a given strength. A second consideration in regard to center of pressure travel is its effect upon stability. With a fixed center of pressure the moment of lift would always be restoring and the moment arm small. The greater the travel of center of pressure, the greater will be the moment arm variation and instability of the wing.

52. **Aspect ratio limitations.**—*a.* In spite of the benefits accru ing from increase in aspect ratio, seldom is it feasible to employ a value greater than 9, owing to structural and parasite drag limitations. Again, owing to the aerodynamic disadvantages of low aspect ratios a minimum value of 4 is the limit except in a few unconventional types. As the value is increased above this minimum the weight of the structure will increase for—

(1) The bending moment will increase since the center of pressure on either side is farther from the wing hinges.

(2) The spar depths will decrease owing to the reduction in chord and less efficient and heavier spars must be employed for the requisite strength.

b. In the case of the cantilever monoplane these influences may eventually dictate abondonment of the cantilever type, but the addition of lift struts augments the parasite resistance which increases as these struts are lengethened to accommodate higher aspect ratios. The angle which these struts make with the wing will eventually become so flat as to lose rigidity of the truss unless undue weight is carried. Consequently, even a change from cantilever to semicantilever construction will not permit employment of abnormal aspect ratios.

c. The same elements are at work with the biplane. The internally braced type will first give way to single-bay trussing with an accompanying parasite drag of struts and wires. As the aspect ratio increases somewhat above 6, the wire pull angles become so flat that rather than increase weight unduly to aid rigidity and take care of bending, a two-bay truss is utilized instead. This must eventually give way to a three-bay truss but at just what point this and the preceding variations will occur depends upon such factors as the airfoil section used, the type of construction, the wing loading, etc.

d. A final consideration with regard to aspect ratio is that the greater its value the greater the span which dictates a longer fuselage to place the tail advantageously for directional stability and control. This lengthening of the fuselage adds weight which must be taken

into account when balancing the advantages and disadvantages of increased aspect ratio.

53. Airflow stability.—Airfoil sections of certain types show instability of airflow over their surfaces as evidenced by pressure distribution irregularities. They are very sensitive to changes in curvature which may come about from slight structural damage, loose fabric, flexure and torsion under flight loads, ice formation, and the like. Other sections show no such tendency, that is, their contours may be strongly modified without appreciable change of characteristics. Obviously, other things being equal the section showing the more stable airflow is the one to employ.

54. Structural adaptability.—The airfoil section chosen from careful study of characteristics must be suitable for the type of construction to be employed. A section clearly acceptable for a biplane may prove unsuitable for a monoplane owing to insufficient thickness to house spars of efficient section. Top and bottom cambers may be so formed as to dictate spar locations at points detrimental to utilization of the wing interior. The type of construction is bound to eliminate certain airfoils which are aerodynamically superior.

55. Operating limitations.—Of the many operating limitations, that of landing speed is the most important. The size of landing fields offers a first limitation. The arresting gear of the aircraft carriers and launching speeds of catapults offer others. The added weight accompanying great span may dictate a change from monoplane to biplane construction or if not this then excessive hangar space is required and more elaborate handling facilities. These and many other operating limitations must not be overlooked when making the selection of the proper airfoil.

56. Airfoil sections.—Airfoil sections are classified as "thin", "medium", or "thick". A thin section is one having a maximum thickness less than 10 percent of the chord. Medium thickness covers a range of 10 to 15 percent, and those above are thick sections. Generally speaking, a medium section is a good compromise. It does not have as low a drag as the thin section nor as high a lift as the highly cambered sections. It does, however, possess lift drag ratios approaching the maximum available.

57. Monoplane vs. biplane.—Were aerodynamic considerations paramount in the design of airplanes, all would be unbraced cantilever monoplanes with tapered wings on the basis of the superior aerodynamic performance of that type. That such considerations are not paramount is evidenced by the large number of biplanes in use and under construction at the present time. Airplanes with more than two sets of wings were employed in earlier times but were eliminated soon

by the demonstrated superiority of the simpler types. The cantilever monoplane remained impractical until a deep airfoil section and more efficient materials were developed, since reasonable structural strength and rigidity could not be secured with the thin sections used in biplanes. Even where strength and rigidity were sufficient in the monoplane, structural efficiency, visibility, maneuverability, and other military features have dictated the use of biplanes in many cases.

58. Biplane pressure distribution.—The airflow between the wings of a biplane combination will differ considerably from what it would be if they were not in close proximity. Interference of the streamlines will exist which reduces the relatively low pressure on the upper surface of the lower wing. This interference is due to the air always wanting to flow from a region of high pressure to one of low pressure. The net result is that, while the lift of both wings is impaired, that of the lower suffers the most, for suction contributes the great percentage of lift. Unfortunately there is no reconciling reduction in drag, the lower wing contributing its portion. While the upper wing carries the greater load the percentage will be dependent on the values of gap-chord ratio, stagger, and decalage employed. These influencing factors will be discussed in succeeding paragraphs.

59. Biplane center of pressure.—The natural conclusion drawn from consideration of the pressure distribution of a biplane is that the resultant lift will be the sum of the lift of each wing and its line of action will be somewhere between the two centers of pressure. The point of application of the lift, however, must be assumed. It is said to be on the mean aerodynamic chord of the combination. This mean aerodynamic chord is the chord of an assumed airfoil section having such a chord length, angle of attack, and so located in the side elevation of the airplane both vertically and horizontally that its airfoil would give the same pitching moments as the combination at all angles of attack. In brief, it is essentially the chord of the equivalent monoplane wing, and will lie somewhere between the chords of the upper and lower wings as indicated in figure 49.

60. Gap-chord ratio.—The distance between the leading edges of the upper and lower wings of a biplane, measured perpendicular to the longitudinal axis of the airplane, is called "gap." This distance is not as a rule employed directly. Rather it is expressed as the gap-chord ratio. The method of measuring gap is shown in figure 51. The lower the gap-chord ratio, the greater will be the interference effects of the airflow and vice versa. However the practical variation of G/c from the value of unity is slight.

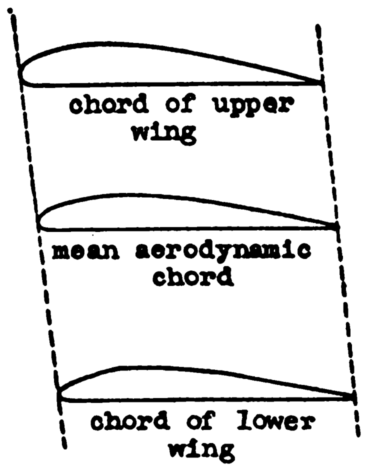


FIGURE 49. Mean aerodynamic chord of biplane.

61. **Stagger.**—*a.* Stagger is the amount which one wing is set ahead of the other. It is positive when the upper wing is in advance of the lower and vice versa. It is measured parallel to the longitudinal reference axis of the airplane, usually between the ⅓ chord points of the mean aerodynamic chords of the individual wings as shown in figure 51. The wide employment of stagger is not due to

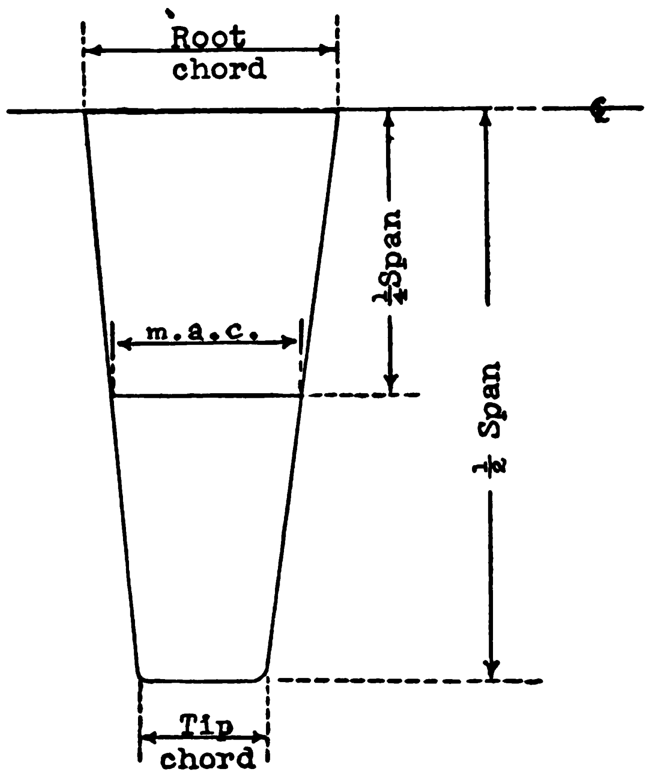


FIGURE 50.—Mean aerodynamic chord for tapered wing.

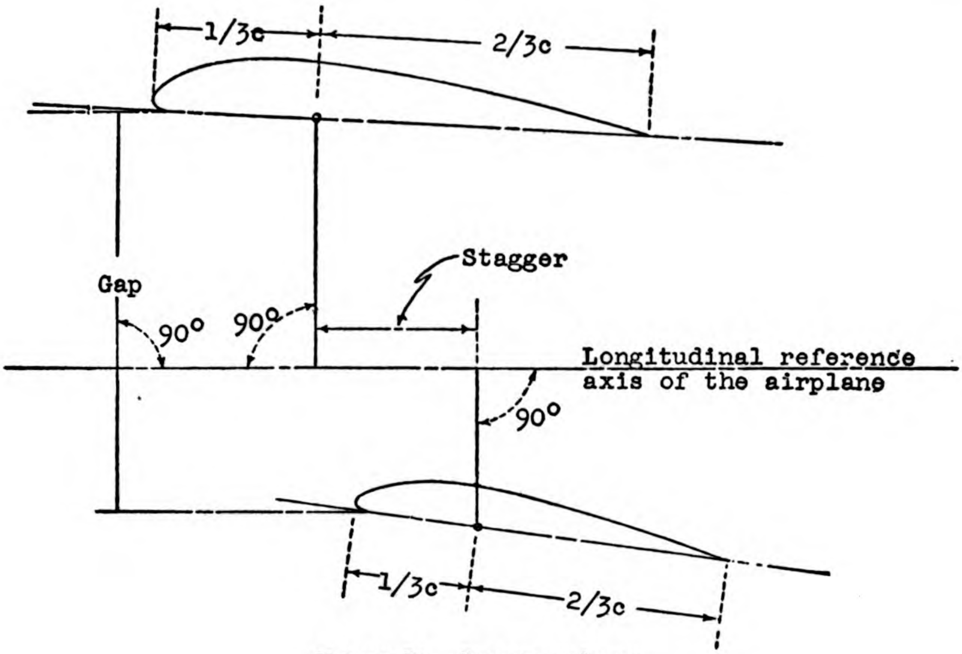


FIGURE 51.—Stagger and gap.

its aerodynamic benefits which are relatively small. Rather it is due to one or more of the following reasons:

(1) Improvement of vision.

(2) Affording of better free gun angles.

(3) Provision for better access to cockpits.

b. Some positive stagger may be necessary to place the pilot's eye in the chord line of the upper wing to minimize the "blind angle"

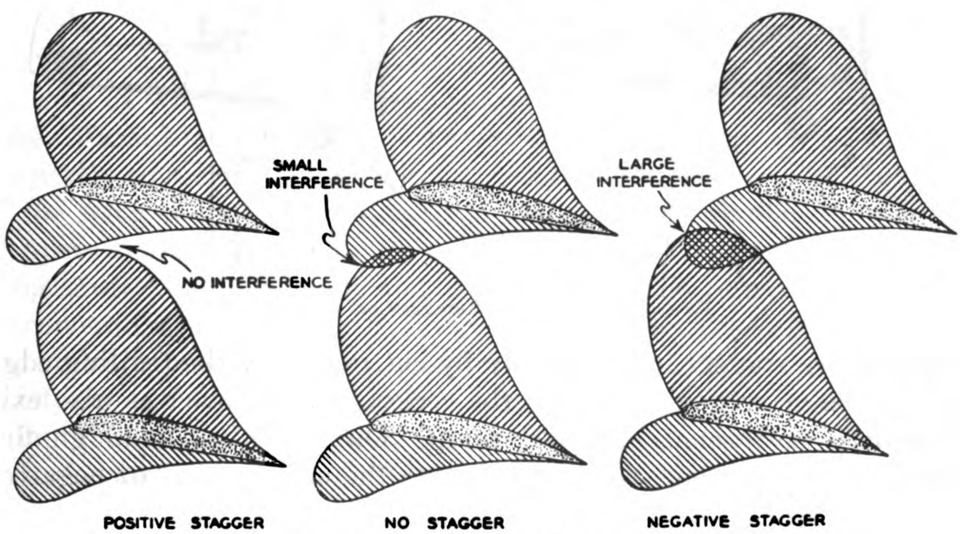


FIGURE 52.—Biplane interference.

forward. With this position fixed, the farther aft the lower wing is moved, that is, the greater the positive stagger, the better will be the vision forward and downward. Negative stagger, on the other hand, may be employed to obtain better gunfire angles forward and downward. Figure 53 illustrates these points.

c. Finally weight and balance considerations may require placing the forward cockpit between the wings of a two seater. By employ-

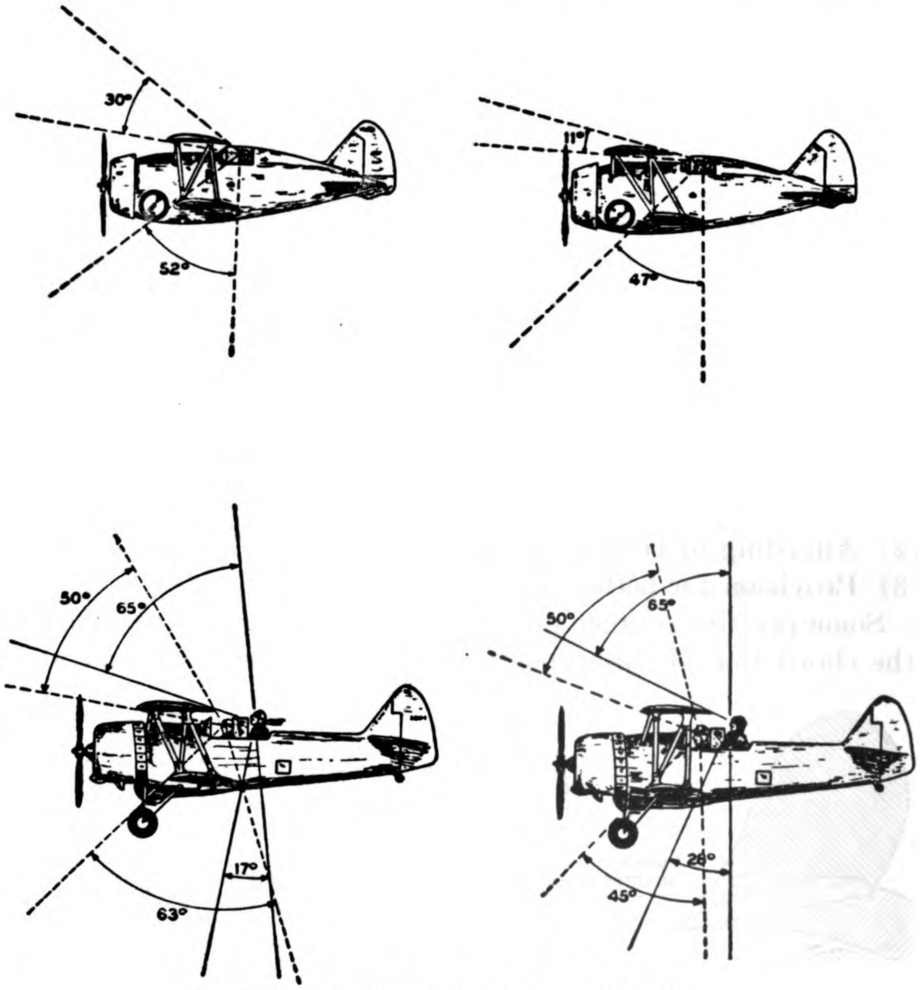


FIGURE 53.—Effects of stagger on visibility.

ing positive stagger, and possibly by cutting away the trailing edge of the center section, access to the cockpit is improved as also exit therefrom in case of a forced jump. On the other hand gunfire angles from the rear seat might dictate the employment of negative stagger.

62. Decalage.—Decalage is defined as being "the difference between the angular settings of the wings of a biplane" or the acute

angle between the extended chords of the upper and lower wings. The N. A. C. A. says that decalage is positive when the upper wing has the greater angle of incidence. When air is passing the wings of a biplane it is deflected downward. If the chord of the upper and lower wings were parallel, the downwash of the upper wing would have the effect of decreasing the angle of attack of the lower. In order properly to distribute the lift between the two wings it is then necessary to set the lower wing at a greater angle. Upper and lower wings being at different angles of attack, the pressure distribution between the wings will be altered. With positive decalage the upper wing will receive an increase in load percentage which is most pronounced at high speed. Negative decalage throws an increased percentage on the lower wing. Since the wings reach their burble points at different angles of attack, the peak of the lift curve for the combination will be flattened and consequently the stall will be less abrupt.

63. Landing speed.—The minimum or stalling speed for the average aircraft is about one-third or two-fifths the maximum speed. This indicates landing speeds approaching 100 miles per hour for fast transports and military airplanes. High landing speed presents a disadvantage in an airplane, first because of the inherent danger in fast landing craft and second, the scarcity of large airports when an emergency landing is in order.

From the fundamental formula for landing speed—

$$V_{min}=\sqrt{\frac{W}{\rho/2S\ C_{Lmax}}} \qquad (38)$$

it is evident that landing speeds can be reduced only by increasing the area of wings or by increasing the maximum lift coefficient.

64. Variable wing area.—Variation in wing area while aerodynamically sound is fraught with structural difficulties. The rigidity of the wing must not be impaired, the necessary additional weight of operating mechanism must not be excessive, the strength of the wing must be maintained, and the shape of the section cannot be detrimentally affected by the variation. While telescoping wings are under experiment there is grave doubt of their ever completely satisfying the above structural requirements.

65. Variable camber.—*a.* The alternative to variation of area is that of variation of lift coefficient. One expedient is to change the airfoil section or camber in flight. Operation on the section as a whole to increase the camber has as great if not greater structural objections than has the variation of area. There remains then the

variation of camber by turning down leading and trailing edges of the wing. Increased curvature or camber will result from turning down either one or both of these edges. This will improve the lift of the airfoil, but naturally not as much as if the curvature were gradual. The drag, of course, is increased, being particularly marked with the trailing edge well down. The rear flap in this position thus constitutes an effective airbrake which affords a steeper descent for landing without increase in airspeed. This is of great advantage in entering a small field over obstructions as illustrated in figure 54.

b. The combination of leading and trailing edge flaps is rarely used. The trailing edge flap, of which there are many variations, is in use to a great extent and is at present the most popular "high lift" device.

(1) The plain flap is similar to ailerons except that the flaps on both sides are lowered simultaneously. The normal plain flap installation on a monoplane is inboard of the ailerons and in a biplane on one wing with ailerons on the other. The plain flap is heavy, hard to operate, and rather inefficient. Its possible applications are limited.

(2) The plain split flap is normally housed flush with the under surface of the wing just forward of the trailing edge. It is simply a flat metal plate hinged along its forward edge. Tests have shown it to be fairly light and effective, but the hinge moments are large and it is difficult to operate.

(3) Zap or Alfaro flaps are similar to the plain split flaps when retracted but the hinge axis is moved aft as the flap is opened to keep the trailing edges of the flap and wing on a line normal to the chord. Zap flaps are more effective and easier to operate than plain flaps.

c. Types of flaps are shown in figure 55. At normal speeds, the flaps being in the up or retracted position, there is no effect upon the lift characteristics of the wing. When the flaps are lowered for landing the lift coefficient curve for the airfoil shows an increase for similar angles of attack of the basic airfoil. The maximum lift coefficient is increased about 70 percent depending upon the type of flaps employed. This is illustrated by the curve in figure 56. In addition to the increased lift there is an increased drag when the flap is down. This increase in drag permits and requires a steeper glide to maintain the reduced flying speed. This increased drag also acts as a brake when the airplane is rolling to a stop on the field. As a hint to pilots, as the airplane approaches to land and the speed is reduced to permit lowering the flaps, the increased drag as the

flaps are lowered may further reduce the speed and permit the airplane to stall. The stall can be prevented by care on the part of the pilot. Also in landing, the stall is rather abrupt due to the high drag as the airplane is leveled off for landing. The high drag reduces speed so rapidly that the airplane is likely to "pancake" unless the pilot is decisive in his landing procedure.

d. The flap in recent use does not entirely satisfy the requirements of a high lift device. Its advantages stated briefly are—

(1) Higher lift coefficient permits a lower speed in landing.

(2) Acting as "airbrákes" the flaps permit a shorter run on the ground in stopping the airplane.

(3) A steeper gliding angle without increase of speed permits clearing of obstructions in landing and also makes spot landings easier.

(4) The use of flaps prevents the tapered wing from stalling at the tip first which is a dangerous characteristic of this very valuable wing plan form.

e. The disadvantages of flaps are such as the following:

(1) The use of flaps requires a particular pilot technique.

(2) Owing to the high drag when increasing the angle of attack it is difficult to control the flight path.

(3) There is always added weight and the possibility of mechanical failure.

(4) The flap is not automatic in operation and the control constitutes another "gadget" to occupy the pilot.

(5) The flap, extending as it usually does along the trailing edge between the ailerons, will, when at full throw, interfere with the functioning of the latter to impair seriously lateral control. Cross wind landings cannot, therefore, be undertaken with impunity.

f. It may be of interest to note that, in the application of flap devices to biplanes, flaps on the lower wing only give a greater increase in maximum lift than flaps on the upper wing only, and that flaps on both wings give a much greater increase in maximum lift than the sum of the two increases, upper and lower. However, when installing flaps on only one wing of a biplane, it is customary to install them on the upper wing since the change in balance of the plane is less.

66. Automatic slots.—*a.* Another way of increasing lift and consequently reducing landing speeds is by preventing the wing from burbling until a greater angle of attack is reached. The automatic slot accomplishes this. It consists of an auxiliary airfoil housed in the leading edge of the wing at low angles of attack but free to move

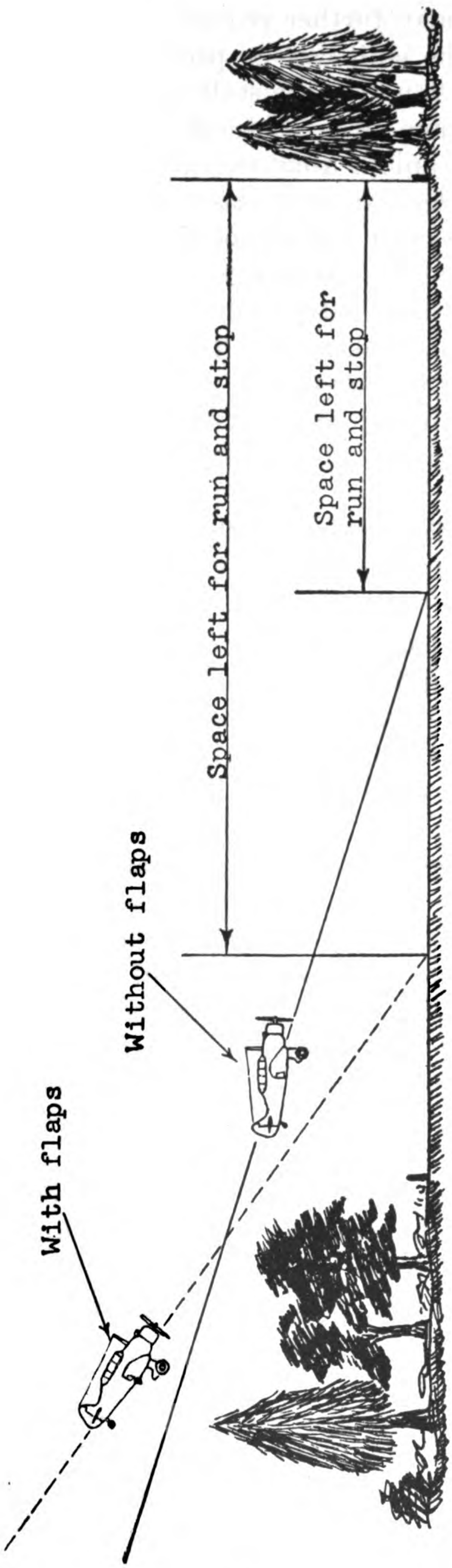


FIGURE 54.—Effect of flaps on landing over obstructions.

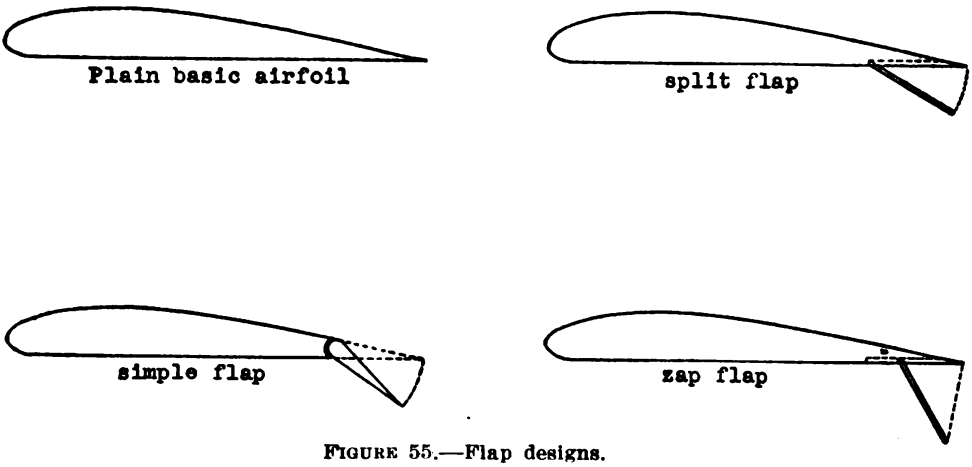


FIGURE 55.—Flap designs.

Angle of attack.

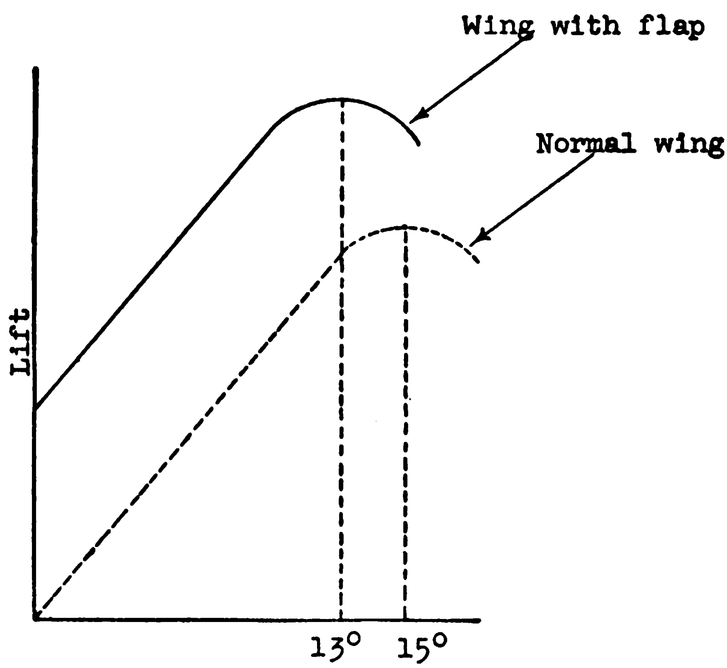


FIGURE 56.—Effect of flap on lift.

forward a definite distance therefrom at high angles to form a flat nozzle or slot through which a portion of the airstream flows to be deflected along the upper surface. The effect of this diverted stream upon the airflow as a whole and consequently the advantage of the device are indicated in figure 57.

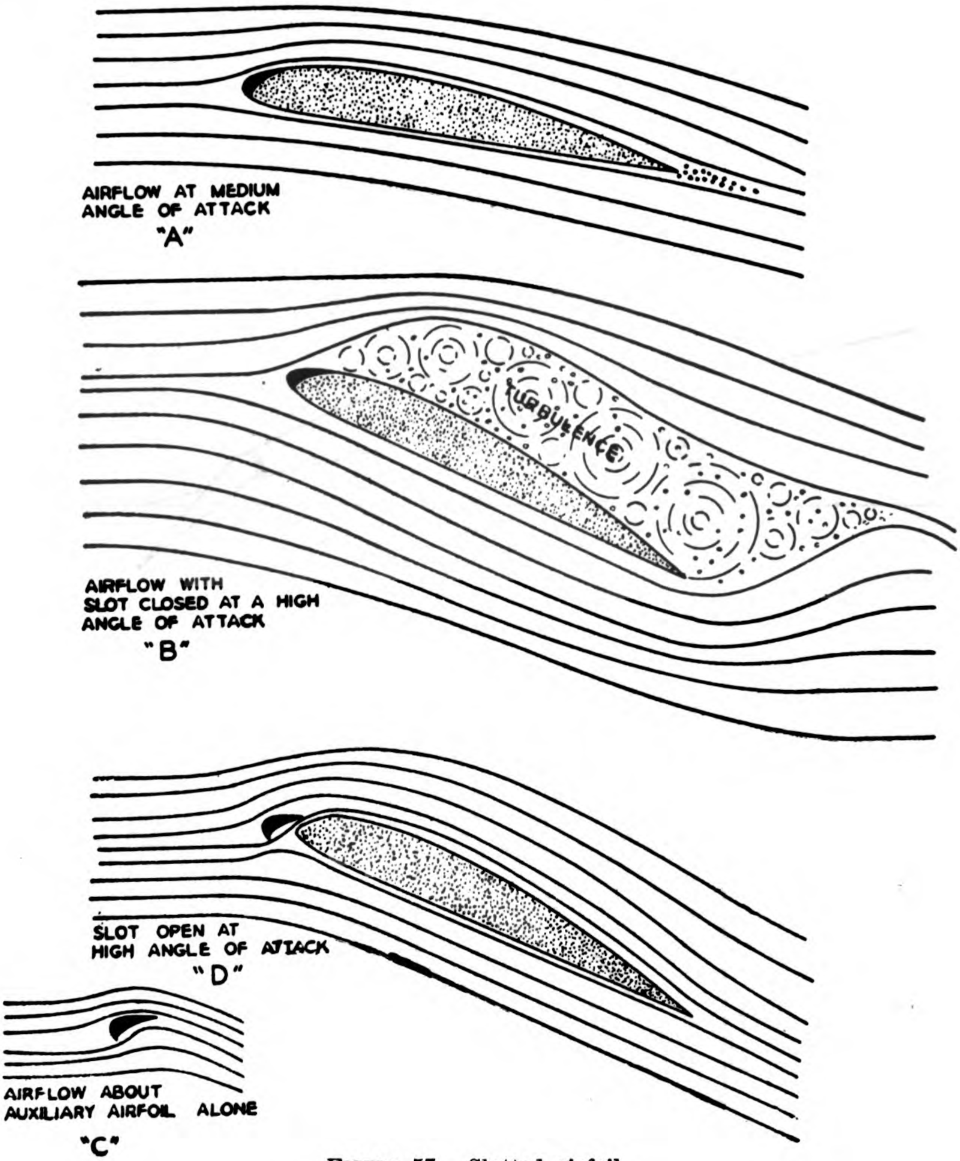
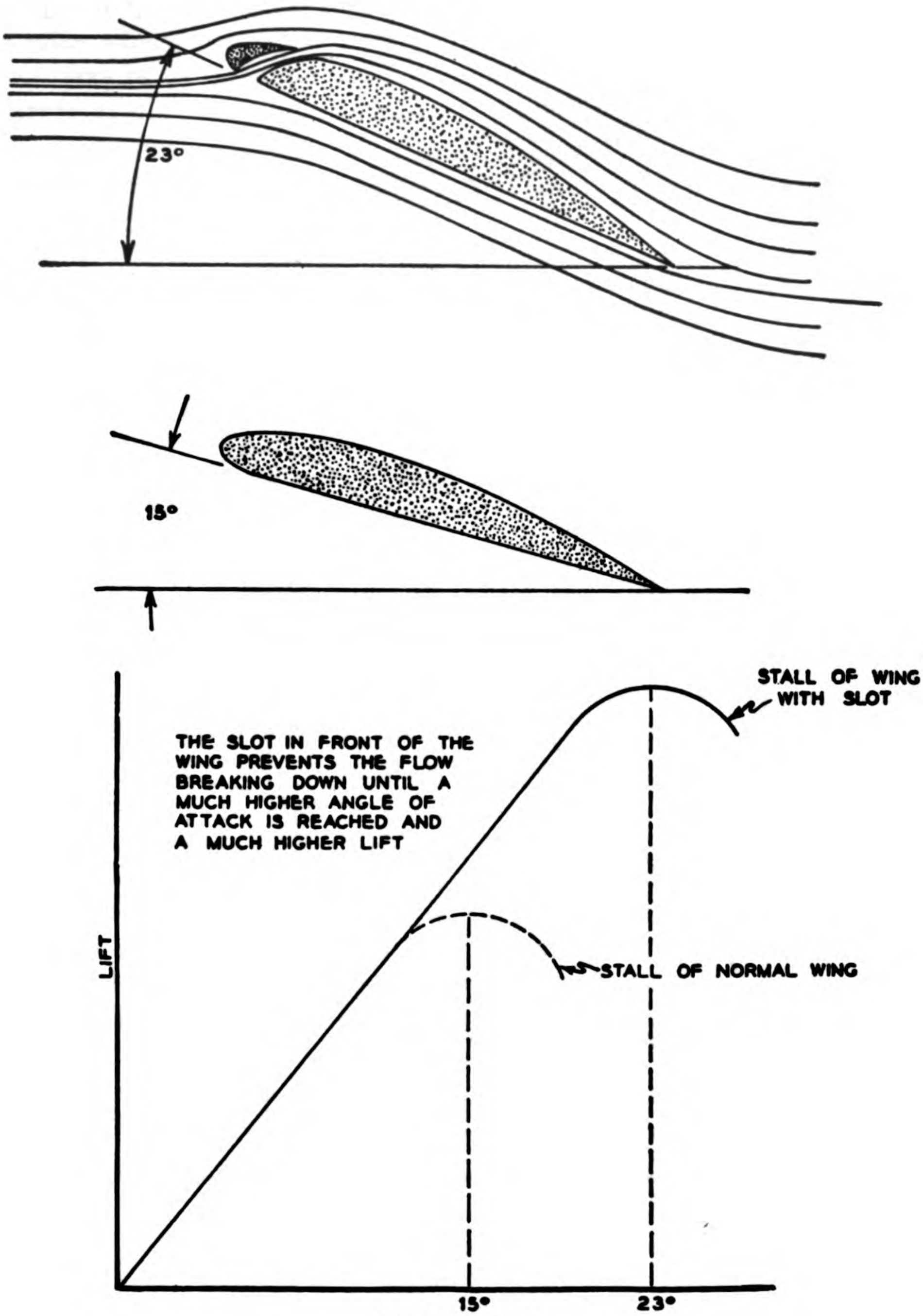


FIGURE 57.—Slotted airfoil.

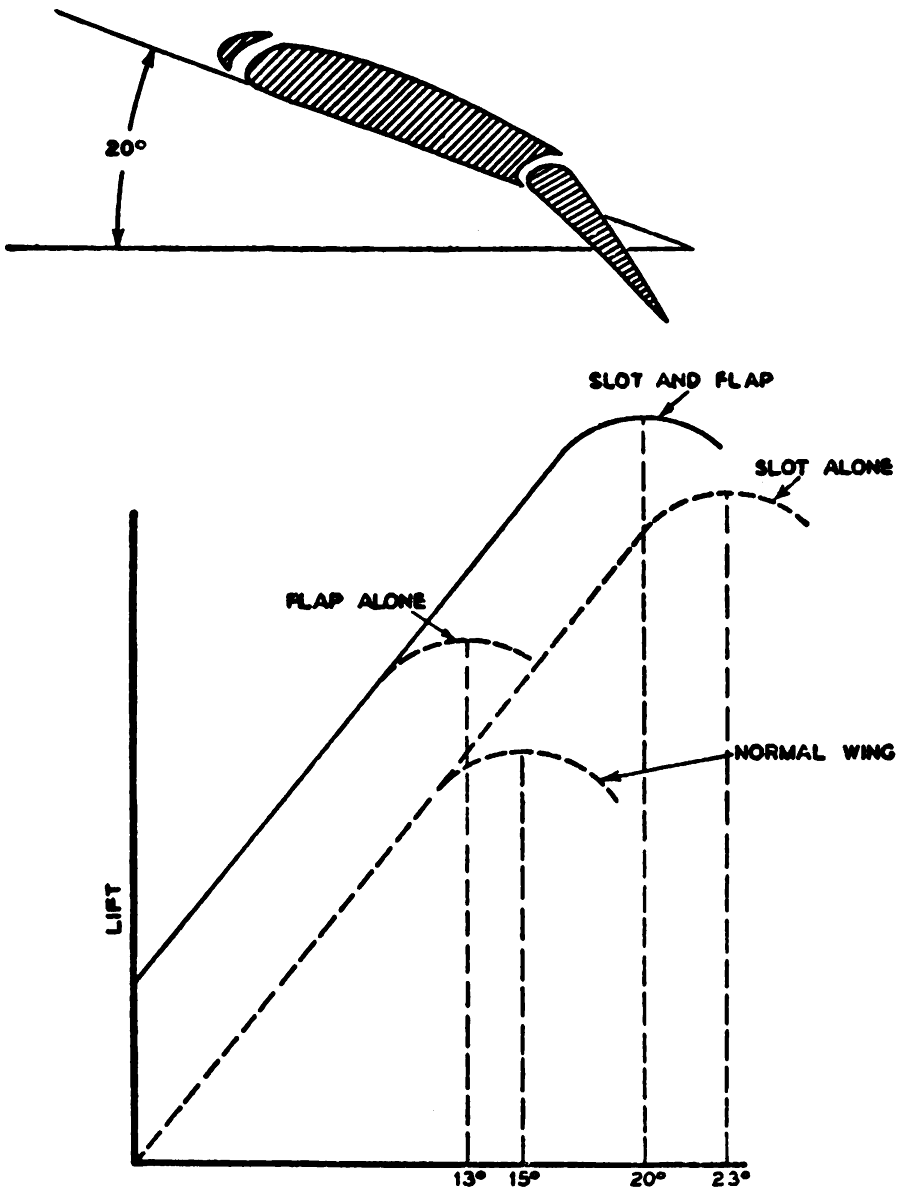
b. The auxiliary airfoil section, derived from the trace of a highly cambered airfoil, is on the leading edge of a normal wing. Were it not free to move, the airflow would be the same as for the normal wing as shown in *A* and *B*. It is, however, free to move on a system of linkages supported by the front spar. Considered alone, the



Angle of attack.

FIGURE 58.—Effect of slot on lift.

airflow about it would be as in *C*. When advanced from the wing at high angle of attack to form the slot, the air will flow through the slot as is obvious from a consideration of the relatively low pres-



Angle of attack.

FIGURE 59.—Slot and flap in combination.

sure above the wing. Being deflected along the upper surface of the wing by the shape of the slot, this inflow of air will postpone the breakdown of streamline flow with increase in angle of attack. The burble point, in fact, will not be reached until the angle of

attack is nearly double that of normal stall where the slot is well-designed and functioning properly. This is shown in figure 58.

c. It is evident from the diagram that the lift is improved at angles where the slot is open and the maximum C_L is not only larger but occurs at a much higher angle of attack. Consequently, the airplane with the slotted wings will have a much lower stalling speed than one not so equipped. But this is not all. The slotted wing is an effective agent for securing lateral stability and avoiding unintentional spins.

d. The automatic functioning of the slot depends upon the pressure distribution with change in angle of attack. It will be remembered that the leading edge is subjected to downloads at low angles of attack and to increasing suction with increase in angle. As long as there is a download the slot will necessarily remain closed. With increase in suction on the auxiliary airfoil, the resultant of all forces on it will finally attain a value and direction sufficient to move it on a properly designed mechanism.

e. For all its advantages the automatic slot imposes disadvantages. Additional weight and moving parts are unavoidable. Weight is further added by the necessity of having longer landing gear struts or oleo legs to eliminate tail skid landings otherwise imposed upon landplanes by the increased angle of attack at the stall.

f. If the slots are not properly fitted or do not operate with equal freedom at opposite wing tips their value is destroyed. They are located on the portion of the wing subjected most strongly to ice formation which, if occurring, will prevent their functioning. With an unbalance from any of the above causes, pernicious spinning may result once it is started and lateral control is difficult.

g. It is, therefore, important that a device be available to lock poorly functioning slots in the closed position. Furthermore, the increased lateral stiffness afforded by the slots makes it advisable to lock them when performing violent manuevers. Such a locking device, controlled from the cockpit, has been developed which adds materially to the service value of the airplanes on which they are installed.

h. In some instances airplanes are equipped with a combination of slots and flaps. This type of installation has many advantages. It permits a much lower landing speed, better control of the flight path, and helps to eliminate nose heaviness caused by the use of flaps alone. The stalling angle of attack differs little from that of the basic airfoil and hence the length of the landing gear legs may remain unchanged.

67. Viscosity.—Viscosity is the tendency of a fluid to stick to surfaces and to resist relative motion by a shearing stress in the fluid itself. The unit of viscosity μ is the force required to move two flat plates relative to each other, each plate being of unit area and unit distance apart.

$$\mu = 373 \times 10^{-9} \text{ lb. sec./sq. ft. for standard air at sea level}$$

$$\text{Kinematic viscosity} = \mu/\rho = 1/6{,}380 \text{ sq. ft./sec. for standard air at sea level} \quad (39)$$

The laws of air resistance thus far discussed are based on the assumption that the forces are due to the scale of the model L, the velocity V, and the density of the air ρ. Forces due to viscosity have been neglected as being so small as to result in no serious error.

The forces due to viscosity give rise to "skin friction," which in cases such as the resistance of airship hulls is a factor that may be

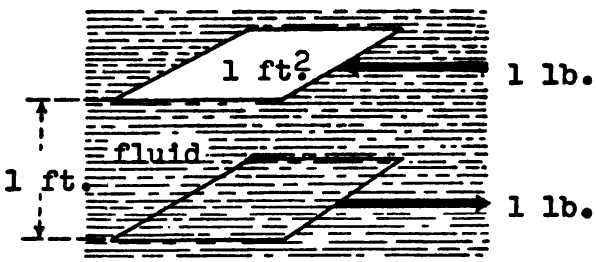


FIGURE 60.—Flat plates separated by fluid of unit viscosity.

larger than the dynamic forces. The laws of skin friction are quite different from the laws governing dynamic resistance.

68. Reynold's number.—*a.* By application of the theory of dimensions, it can be shown that the quantity $Vl\rho/\mu$ (Reynold's number) is the factor that may be taken as a measure of the effects of viscosity. This is also referred to as "scale effect." V is in ft./sec., l in feet (customarily the chord of an airfoil) and ρ/μ (for standard air) = 6,380. sec./sq. ft. Thus the Reynold's number for an airplane with a chord of 10 feet at a velocity of 180 m. p. h. (264 ft./sec.) is

$$\text{R. N.} = 6{,}380 \times 10 \times 264 = 17{,}000{,}000 \quad (40)$$

b. If wind tunnel data are to be useful to the airplane designer, the Reynold's number of the wind tunnel test must be of the same general magnitude as the Reynold's number of the full scale airplane. If a small scale model is used in the wind tunnel, one way of keeping the Reynold's number constant is to increase the density of the air as is

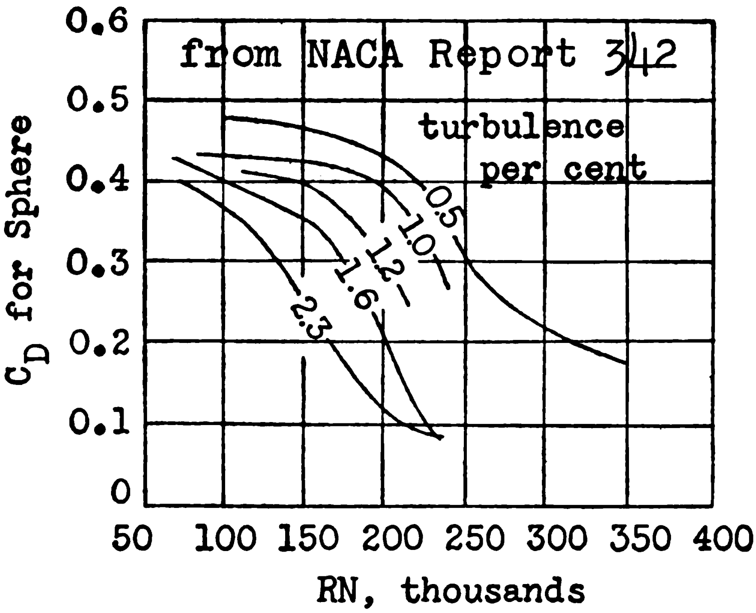


FIGURE 61.—Effect of scale on drag coefficient.

done in the National Advisory Committee for Aeronautics variable density wind tunnel where tests are run at densities as high as 20 times the standard density.

c. In applying wind tunnel test data obtained from small models to full scale airplanes, the following effects can usually be expected:

(1) Lift coefficients are not materially affected by scale effects (except $C_{L\ max}$.)

(2) The drag of the full scale airplane will be considerably less than predicted.

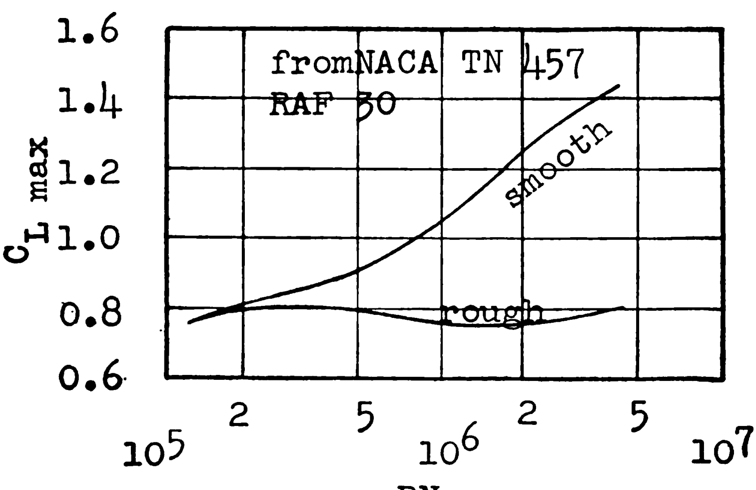


FIGURE 62.—Effect of surface.

(3) **Center of pressure travel is not materially affected.**

(4) $C_{L\,max}$ and the shape of the lift curve at $C_{L\,max}$ may be materially affected by the Reynold's number.

(5) The appearance of unstable airflow and the change from streamline flow to turbulent flow are greatly influenced by Reynold's number.

(6) Parasite resistance is greatly affected by Reynold's number, in general being less than predicted with increase in *RN*.

(7) Profile drag coefficient C_{D_0} decreases with increase in *RN*.

69. **Boundary layer effects.**—*a*. Mathematicians imagine an ideal frictionless fluid which slips past solid surfaces with perfect ease. The real fluid, air, cannot slip past in this way. Due to its viscosity, it sticks to the surface of solid bodies and its velocity falls

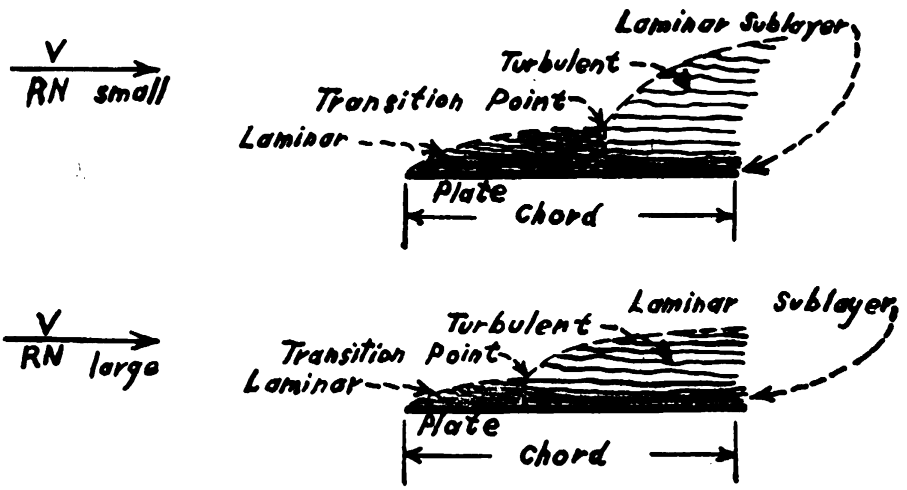
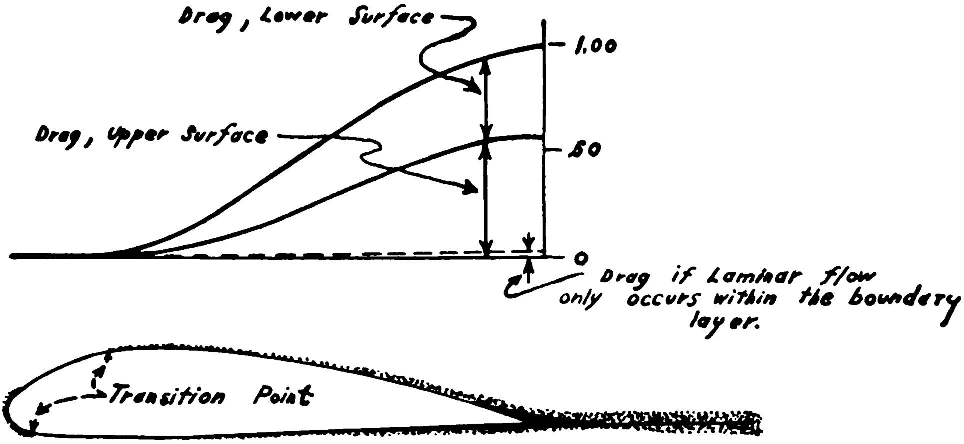


FIGURE 63.—Transition from laminar to turbulent flow in boundary layer on a flat plate.

to zero as the solid surface is approached. The layer of fluid surrounding the solid surface, in which this velocity fall takes place, is called the "boundary layer", and with large bodies of good streamline form moving fast it is relatively thin. *Skin friction* is the drag force which depends upon what happens within the boundary layer. It is due to the viscosity of the fluid.

b. The form taken by the boundary layer about a wing does not differ greatly from the boundary layer upon a flat surface which has been extensively studied both experimentally and theoretically. Figure 63 indicates a boundary layer on a flat surface, the vertical scale being greatly exaggerated. The thickness of the boundary layer and the amount of drag incurred in it remain very small for some distance

from the leading edge of the surface. In this forward part of the layer, the flow is called "laminar", that is, separate sheets, or laminae, of air overlie the solid surface and slide over one another without mixing. At the transition point, relatively rapid thickening of the boundary layer begins, the flow within the layer becomes irregular (turbulent), there is a thorough mixing of air from different levels, and the resulting drag is relatively large. Beneath the turbulent part of the boundary layer is an exceedingly thin viscous sublayer within which the velocity gradient is very great and the airflow returns nearly to the laminar form. The importance of this viscous sublayer lies in that it appears that, provided the roughness on the surface over which the air flows does not protrude beyond the viscous sublayer, it has no effect upon the turbulent outer parts of the boundary layer through which drag is conveyed from the main stream, and hence



The inner edge of the black line defines the surface of the wing which is not otherwise represented. The thickness of the boundary layer is represented by the black line and the shaded area.

FIGURE 64.—Boundary layer about a wing in flight.

it has no effect upon the skin friction. When a surface is sufficiently rough that the projections on it penetrate beyond the viscous sublayer, the main turbulent layer is increased and with it the skin friction. Surface irregularities such as rivet heads, lapped jonts, and spot welds may increase wing drag sufficiently to have important adverse effects on high speed airplane performance. This is the more readily understood if it is realized that the thickness of the laminar sublayer may be on the order of 0.0002 inch at the Reynold's number of maximum speed in flight, so that irregularities which project farther from the surface than this value will increase the drag due to skin friction.

c. In figure 64 is a representation of the boundary layer and wake of a wing in flight, together with the points of transition

from laminar to turbulent flow and curves showing the drag incurred in the boundary layer up to each point on the profile. The dotted line indicates the skin friction drag which would be incurred

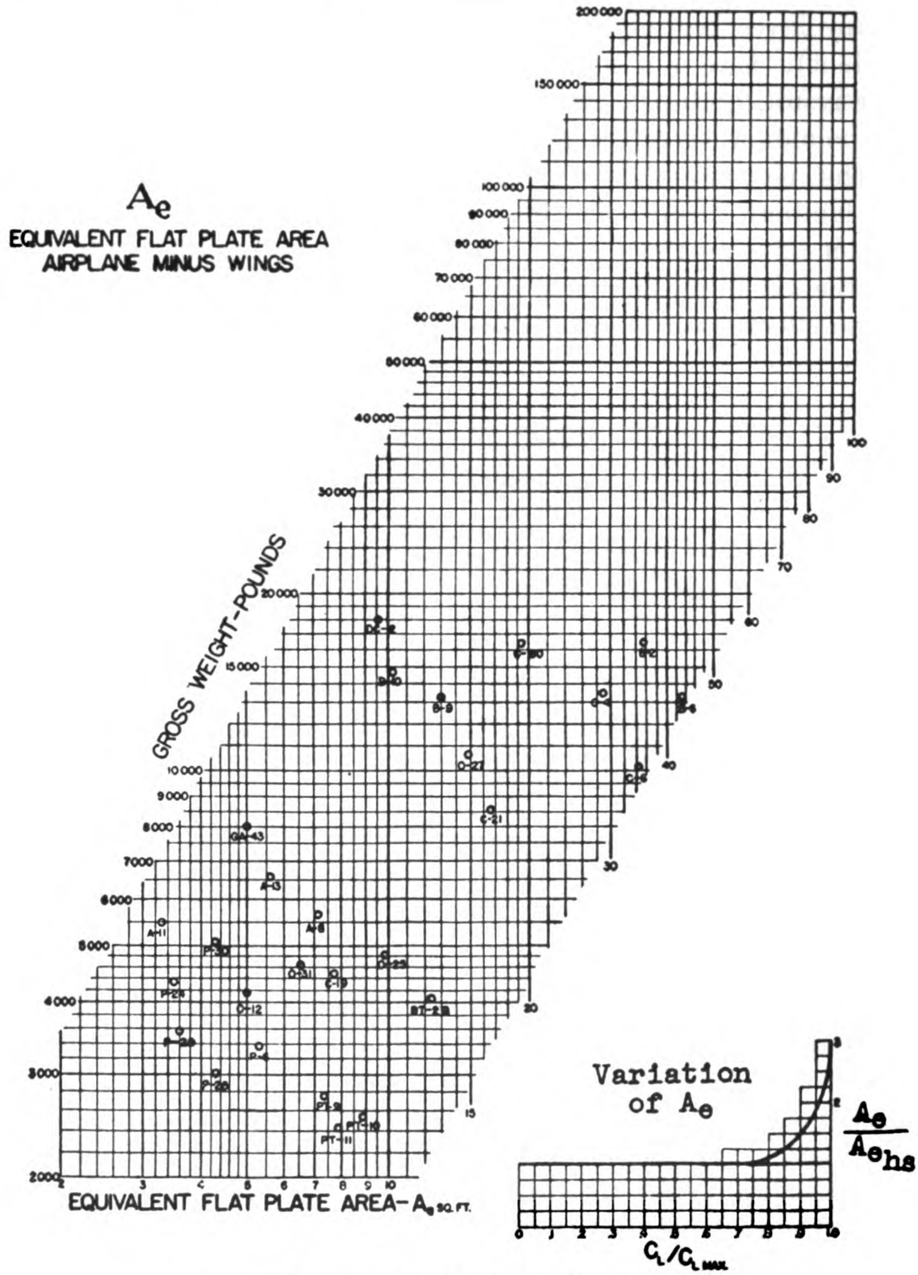


FIGURE 65.—Equivalent flat plate area.

if turbulent flow could be suppressed so that skin friction drags would occur in an entirely laminar boundary layer. It is apparent from the diagram that any factors which will postpone transition

to turbulent flow to a point farther along the profile from the leading edge will result in greatly decreased profile drags. The location of the transition point is affected by several variables, among which are the Reynold's number, turbulence of the free air, curvature of the surface, and the roughness of the surface. It is known that the free air is remarkably free from turbulence on a scale tending to transform the laminar flow of the boundary layer to turbulent flow, and that it is possible to postpone the transformation to turbulent flow to points sufficiently far from the leading edge of wings that large reductions in profile drag occur. Since at low angles of attack the greater part of the wing drag is profile drag, marked increase in high speed performance accrues from all measures which result in delaying the transition from laminar flow to turbulent flow in the boundary layer.

SECTION IV

PARASITE DRAG

70. Skin friction and form drag.—*a.* Parasite drag is composed of two distinct elements, the drag of *skin friction* in the boundary layer, and the *form drag* due to disruption of streamline flow and the resulting turbulence. The skin friction component results from the interaction between a viscous fluid and the surface of the solid which may be either smooth or rough. The form drag due to disruption of the streamline flow depends upon the extent of the disruption of the streamlines and the resulting turbulence. Thus the drag of a flat plate is practically all skin friction when edgewise to the airstream but when normal to the airstream the drag is due almost entirely to disruption of the streamline flow.

b. A low parasite drag is of utmost importance in airplane design, for every pound of drag requires a pound of thrust from the propeller to maintain the relative motion necessary for sustentation. Each pound of thrust so used adds to the engine power required and to the fuel consumption as well.

c. Of the two components of parasite drag, that due to disruption of the streamline flow affords the greatest opportunity for reduction. On modern high performance aircraft, streamlining is so effective that the form drag is often less than the drag of skin friction. It is therefore important that skin friction be made as small as possible. The area of surfaces exposed to the airstream is fairly well fixed by structural requirements of strength, housing capacity, and the like. Skin friction can be minimized by employing a glossy flat finish to surfaces and eliminating protruding rivet heads, roughness, and other surface irregularities.

71. Parasite drag coefficient.—Parasite drag is a resistance and as such can be expressed by the same sort of fundamental equation as that employed for lift and drag of the wings:

$$D_p = C_{D_p} \rho/2 A V^2 \tag{41}$$

where C_{D_p} is the resistance coefficient for the particular item under consideration, A the projected area of the body in square feet or the area of its largest cross section taken in a plane perpendicular to the relative wind, and V the velocity of the airstream in feet per second. The determination of the resistance of segregated items over a range of airspeeds would prove an exhaustive task where the total of such items represents the parasite members of an airplane. Fortunately a simplifying expedient is available which materially reduces the labor of parasite drag determination. This is the expression of all parasite drag items in terms of the equivalent flat plate area for a particular airspeed.

72. Equivalent flat plate area.—*a.* A flat plate, if approximately square and of some 12 square feet or more in area, will be found to have a resistance coefficient of 0.00152 when placed at right angles to an airstream. Therefore

$$\text{Flat plate drag} = 0.00152\ AV^2 \tag{42}$$

b. By equivalent flat plate area is meant the area of a flat plate normal to an airstream which will give the same drag as the body or bodies placed in the same stream. Thus if the sum of all parasite

items gives a drag of, say 228 pounds, at 100 ft./sec. the equivalent flat plate area will be

$$A_e = \frac{228}{0.00152 \times 100 \times 100} = \frac{228}{15.2} = 15 \text{ sq. ft.} \tag{43}$$

c. For any other airspeed, then, the parasite drag will be

$$D_p = 0.00152 \times 15 \times V^2 \tag{44}$$

and at 60 ft./sec is 0.00152×15×60×60=82 lbs. The labor of determining the individual resistance and summing these up to obtain the total parasite drag is thus saved for this and any other speed by employment of the equivalent flat plate area.

d. It will be noted that in the above calculations, standard air is assumed and the factor $\rho/2$ is incorporated in the parasite drag coefficient 0.00152.

73. Parasite drag and model tests.—*a.* The above method of determining the parasite drag serves well for preliminary design but it should be checked by resistance data on the complete model. Corrections must be made for parts eliminated from the model and the wing drag must be subtracted from the measured total to obtain the parasite value. This in turn must be scaled to full size or

$$D_p = D_{pm} \times \frac{1}{(\text{scale of model})^2} = \frac{V^2}{V_m^2} \tag{45}$$

where the subscript m indicates the model values, and the scale, any linear dimension of the model to that of the full sized airplane.

b. Parasite drag is particularly sensitive to changes in Reynold's number, and an attribute of the successful airplane designer is a knowledge of the limitations of model test data in its application to the full scale airplane.

c. Since the total drag of an airplane must equal the thrust, its value for those actually built can be readily determined from flight test for the high speed condition where the engine is operating at its rated horsepower and the propeller at its maximum efficiency as discussed in later sections. By subtracting computed wing drag from the maximum thrust, the parasite drag is determined. This may be expressed in terms of equivalent flat plate area, and thereafter the parasite drag at other speeds may be readily calculated. The value of knowing this drag for airplanes in service lies primarily in being able to prognosticate closely that of similar ones in the process of design. By making due allowance for differences in truss-

ing, fairing, etc., the experienced designer need not undertake the laborious calculations incident to summing up individual drag items.

74. Interference.—*a.* None of the above methods of parasite drag determination take cognizance of specific interference effects between adjacent bodies. Two wires, one behind the other, may show less drag than a single wire. If side by side and spaced less than 6 diameters they will show more than twice the resistance of a single wire. The result depends entirely upon whether turbulence is reduced or increased by the close proximity of the bodies.

b. Most pronounced, however, is the effect of bodies attached to or protruding from the wing. The turbulence resulting will give interference drags ranging from 50 to 200 percent greater than those of the parts tested separately.

c. The method usually applied by the Navy for estimating drag is by summing the drags of the component parts of the airplane at a specified speed. The Army prefers a shorter method which consists in the estimation of equivalent-flat-plate area of the complete airplane at high speed. This method consists of comparing airplanes being designed with airplanes already constructed whose equivalent flat plate areas have been determined by flight tests. Likewise an estimate of the variation of parasite drag coefficient depending upon the particular shape of fuselage to be used is made from an examination of photographs and detailed drawings of existing airplanes. These estimates are then checked against and compared with the data presented.

75. Slipstream effect.—The airplane propeller in producing a forward thrust must impart to the air a change in momentum in accordance with Newton's laws. The air affected is that which is drawn through the propeller and pushed aft, constituting the slipstream. The velocity of the slipstream varies with throttle setting and angle of attack, and is of the order of 10 to 15 percent more than the airspeed for normal flight at full power and some 40 percent for steep climb at full throttle. Obviously all parts of the structure exposed to the slipstream will have their drags increased over that which would obtain if no acceleration had been imparted to the air driven aft by the propeller. Account must be taken of this in determination of parasite drag. It is customary to compute A_e from the high speed performance test of the complete airplane, and to consider that the velocity of the slipstream has a negligible effect on the parasite resistance at the high speed condition of flight.

76. Struts.—*a.* The struts of an airplane are the structural members which are primarily subjected to compression loads. Where

exposed to the airstream, as are the interplane members of the wing cellule, struts should be streamlined to minimize drag. A streamline form is defined by its fineness ratio. The fineness ratio of a body is the ratio of its dimension in the direction of the airstream to the maximum dimension perpendicular to the airstream. Thus the strut section shown in figure 66 has a fineness ratio of 3.

b. Though tubing of circular cross section and built up struts of the so-called "Eureka" section shown in figure 67 give higher compressive strength values for a given weight they offer more resistance than a

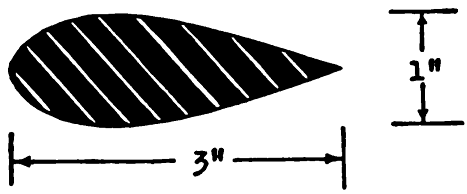
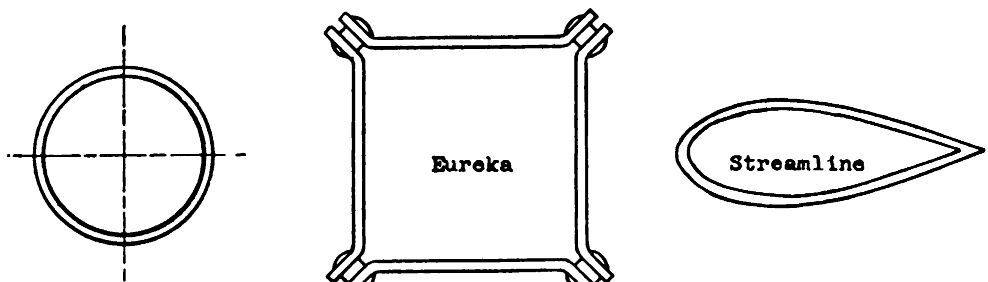


FIGURE 66.—Typical strut cross section.

streamlined shape such as depicted. The Eureka section can be ruled out as being bound to evidence more turbulence than a flat plate. The drag of the circular cross section per foot length is expressed by the equation

$$D \text{ (per ft.)} = 0.00012 \times \text{Dia. (inches)} \times V^2 \qquad (46)$$

That of a streamline form is the same except for lower values of the coefficient which range from 0.000009 for a fineness ratio of 2.5 to



Circular

FIGURE 67.—Types of strut cross section.

0.000008 for a fineness ratio of 4.0. Thus the drag of a strut of circular cross section is $0.00012 \div 0.000008 = 15$ times that of a streamline section of fineness ratio of 4. It is little wonder then that light fairings are employed on tubes of circular cross section where the cost of streamline tubing is not considered justified. Typical examples of fairing are shown in figure 68.

77. Wire and tie rods.—The usual tension members of the airplane structure are wires and tie rods, the distinction being in the

terminal employed. The tie rod uses a threaded terminal whereas the wire uses a spliced, wrapped, or ferruled one. Tie rods or solid wires of circular cross section will have a drag calculable from the same formula as that of the round tubing. Stranded cable, however, owing to its rough surface will have a higher resistance coefficient, that is, 0.00015. Hence the latter offers practically 20 percent more drag than the solid wire or round tie rod. Streamline tie rods show a much lower drag than do those of circular cross section as would be expected after noting the differences in the case of struts. These tie rods are not of true streamline section, however, for rigging requires a definite tension which might place the trailing edge forward and ruin the low drag characteristic. In consequence, the cross section is lenticular as shown in figure 68 which indicates the usual proportions. Obviously, either edge may be the leading edge. The drag is only 15 percent that of the tie rod of circular cross section but this holds only as the long axis parallels the airstream. Should such a rod be placed athwartships, not only would the resistance increase excessively but serious vibration would be set up.

78. Fittings.—A fitting will have a drag varying from approximately 70 percent that of a normal flat plate of equal projected area to that of a flat plate of double its projected area. The higher value will occur where the fitting is so attached as to be subjected to considerable interference. Careful design of fittings has brought about a reduction of drag from 50 to 75 percent or where an obsolete fitting shows a 4-pound drag at 100 m. p. h. a modern one will show a little over a pound. It is no wonder even with this lower value that the present day tendency is to conceal fittings as much as possible to minimize the drag. This is indicated in figure 68.

79. Bare fuselage.—The bare fuselages of most modern airplanes show a resistance coefficient which is but a fraction of that of a flat plate. This is due to the low resistance form now generally employed. An average value of drag coefficient, with all projections, windshields, engine, radiator, and the like removed, is approximately 0.0002; where the lesser items are considered, the value of drag coefficient will average about 0.00025. However, when great refinement is undertaken the coefficient may be reduced to about one-tenth that of the flat plate, or 0.00015. Nacelles show resistance coefficients essentially the same as those for fuselages.

80. Fuselage with appendages.—The addition of windshields will ordinarily increase the resistance coefficient value somewhat though such is not always the case. Where the windshield is well

formed, this increase may be negligible even with the pilot placed behind it. In general, miscellaneous projecting parts which are not streamlined may be treated as fittings. These may include hand fire extinguishers, compasses, airspeed meters, altimeters, etc. Obviously, wherever possible, such items of equipment should be housed inside the cockpit for each offers one or more pounds of drag at 100 ft./sec.

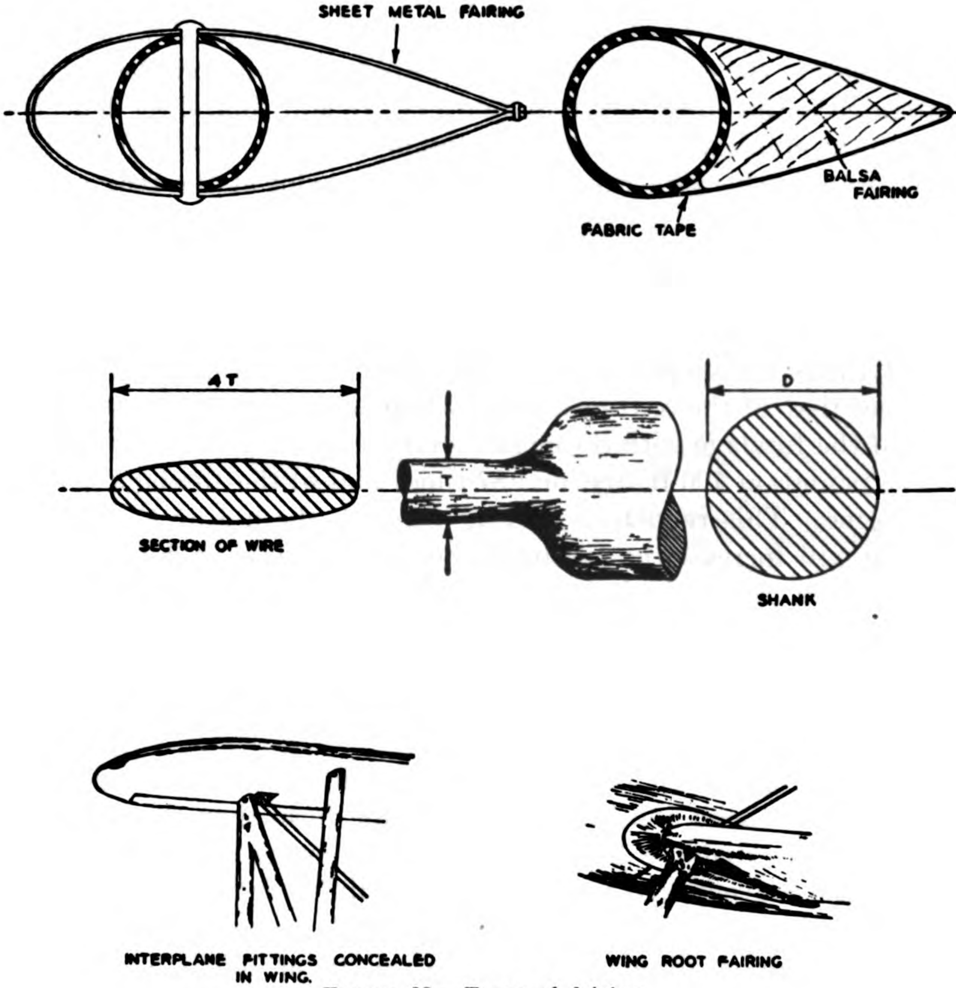


FIGURE 68.—Types of fairing.

81. Fuselage with engine.—The contribution of appendages to the bare fuselage drag is practically nothing compared to that of an engine housed conventionally in the nose. An engine, so placed, requires a blunt nose and ordinarily takes such a form that the streamlines are badly disturbed and the resistance coefficient, in consequence, greatly increased. It has been found from full scale tests that the drag of a bare cabin fuselage with engine removed and nose rounded

is less than one-third that evidenced when a radial air-cooled engine is in place. In this instance the drag was 18 pounds as against 57 pounds at 100 ft./sec. In general, the drag of an open cockpit fuselage is some 10 percent higher.

82. N. A. C. A. low drag cowling.—The high drag of the static radial air-cooled engine, caused by its large frontal area and poor aerodynamic form, has militated against more universal adoption. The N. A. C. A. "low drag" cowling has overcome this disadvantage. This cowling consists of a sheet aluminum nose or hood which completely covers the engine except for an air intake around the shaft as illustrated in the lower sketch in figure 71. In addition, sheet deflectors close to the crankcase divert the airstream to those parts of the engine which would otherwise run hot. An annular slot at the rear insures that the air in leaving will flow smoothly along the fuselage. Such a cowling offers as little disturbance to streamline flow over the fuselage as possible. The air for cooling the engine is separated from the general flow and then fed back smoothly through the slot. Consequently, it is not surprising that the reduction in drag is better than 2.5 times that of the conventional cowling with a large spinner. The drag of the fuselage with the engine so cowled in a particular instance was 34 pounds at 100 ft./sec. or 1.87 times that of the fuselage without the engine. This reduction in drag through the use of N. A. C. A. cowling will increase the maximum horizontal speed at full power of conventional cabin airplanes from 5 to 10 m. p. h., and small open cockpit airplanes from 15 to 20 m. p. h. Furthermore, the power available for climb will be greater, the rate of climb improved, and the ceiling raised. Finally the fuel consumption will be less and the range increased in consequence.

83. Fuselage with radiator.—*a.* The liquid-cooled engine has a smaller frontal area and better aerodynamic form than the air-cooled radial, so it contributes less drag. This is more than made up, however, by the conventional radiator. This cellular or honeycomb radiator is usually placed in the nose or on the side or bottom of the fuselage. An average drag value is 8 lbs./sq. ft. at 100 ft./sec. though the resistance varies with the depth. Thus a radiator with 5-inch tubes has a drag of approximately 3/8 that of a flat plate of equal frontal area and one with 9-inch tubes about 1/2. With the shutters closed, the coefficient will be the same as for a flat plate. Owing to the high drag offered by such radiators other types are sometimes employed. In the wing and float radiators used on racers, parasite resistance is practically eliminated since the water is cooled by contact with a surface already a necessary part of structure. This is indicated in figure 69.

b. Maintenance and operating problems of these radiators are such as to discourage their general use. The "core" type is the one preferred. It remains then to employ a radiator of such a type but of smaller frontal area and less depth. This is feasible only by using a cooling liquid which boils at a higher temperature. Such a liquid must, furthermore, have a relatively high flash point, a relatively high specific heat, and good surface wetting qualities. Finally, it must not attack the material with which it comes in contact nor be decomposed itself. Ethyline-glycol, marketed under the trade name of "Prestone," complies with these requirements and permits more

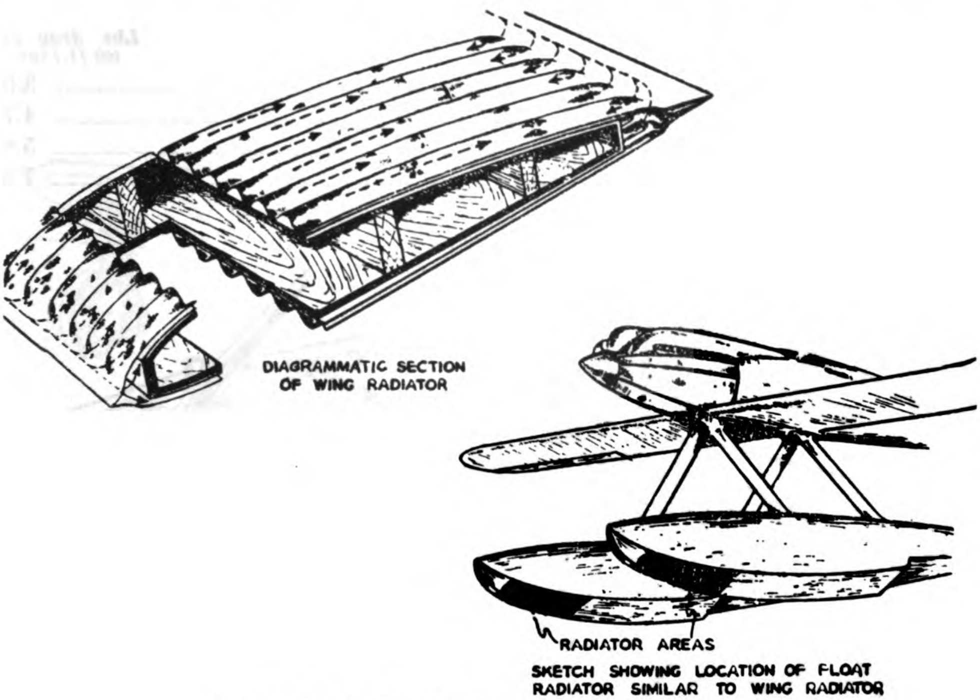


FIGURE 69.—Types of radiators for racing airplanes.

efficient operation of the modern airplane engine than when it is water-cooled.

c. While operation of an engine at 300° F. entails a loss of some 3 percent in power, this is more than counterbalanced by—

(1) Better fuel economy.

(2) Reduction in radiator size.

(3) Reduction in the amount of cooling liquid necessary.

(4) Reduction in weight of engine installation.

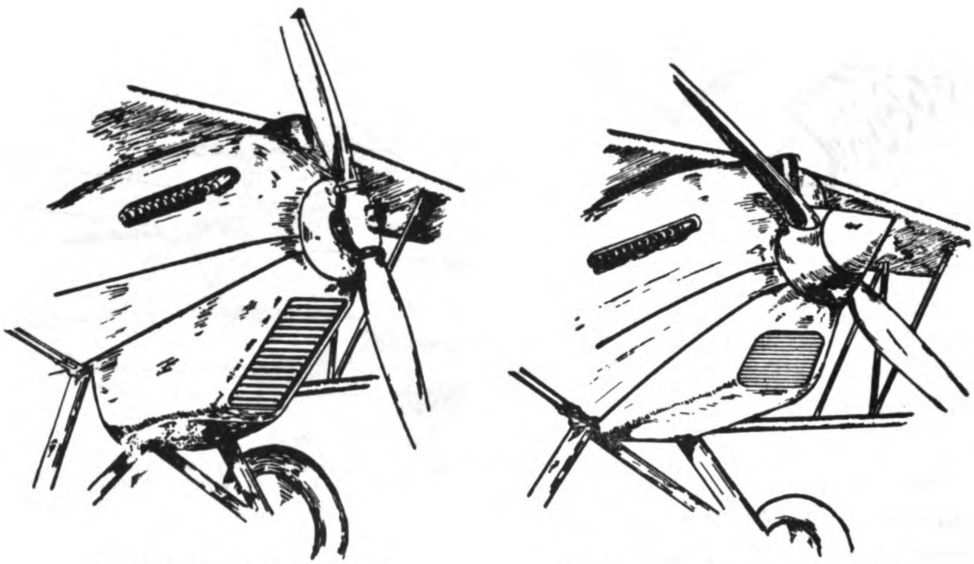
(5) Reduction in the parasite drag of the airplane.

(6) Simple and positive provisions for ample heating of the inlet manifolds.

These advantages are all interrelated, but, with respect to parasite drag directly, certain facts are outstanding. The radiator normally offers about 15 percent of the total parasite drag of the airplane. With Prestone the radiator cooling surface can be 70 percent less than that required with water-cooling. Such a reduction in frontal area should result in a radiator parasite drag of 4.5 percent of the total instead of 15 percent. An idea of the relative sizes of water-cooled and Prestone cooled power plants can be obtained from figure 70.

84. Wheels.—*a.* The following table gives the approximate drag in pounds per wheel for standard sizes:

Size of wheel:	*Lbs. drag at 100 ft./sec.*
26 x 3	3.5
28 x 4	4.7
30 x 5	5.8
32 x 6	7.5



Equipped for water cooling Equipped for "Prestone" cooling

FIGURE 70.—Conventional radiator installation.

Obviously, the fairing of wheels is worth while for the reduction of drag.

b. For the conventional spoke type wheel, light metal sheets are employed in fairing. With the disk wheel, side plating serves as part of the wheel structure and constitutes its own fairing. Such fairing does not constitute the most that can be done in this respect. Figure 71 indicates the refinements resorted to in reduction of wheel drag. In general, however, it can be said that some 40 percent of the landing gear drag is due to the wheels.

85. Retractable and detachable landing gears.—*a.* A retractable landing gear is one which can be actuated so that it may be housed snugly in the structure to minimize resistance in flight. In

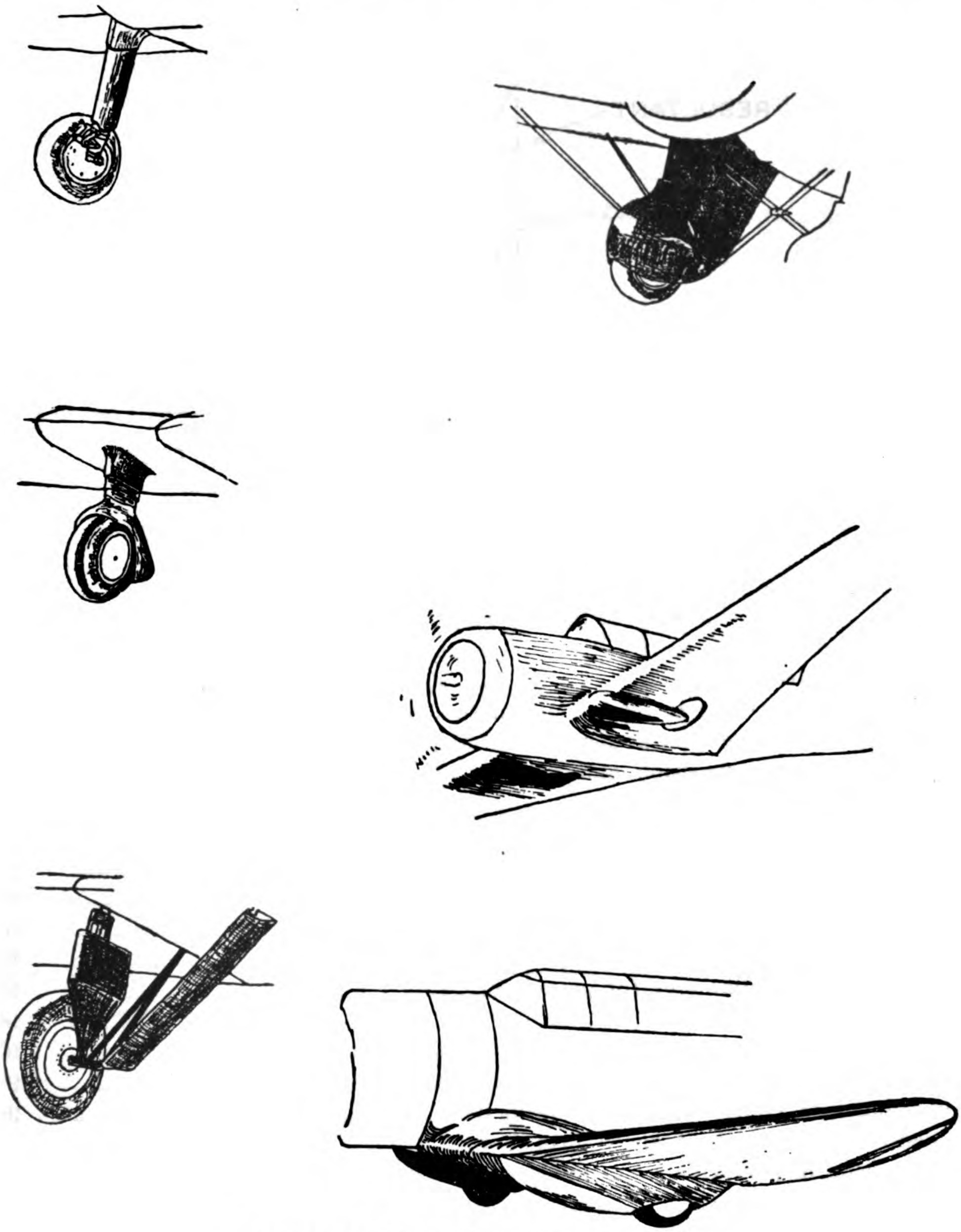


FIGURE 71.—Types of landing gear design.

one instance an increase of 55 m. p. h. with the landing gear housed as against what it was when extended was observed.

b. Detachable landing gears are not installed on service type airplanes at this time. Their use, however, might improve performance

in combat after dropping. This type of landing gear has been installed on a number of airplanes used in long distance and transoceanic flying to reduce weight and resistance after take-off. Justification for their use might lie in their minimizing overturning tendencies of landplanes forced to alight on the water.

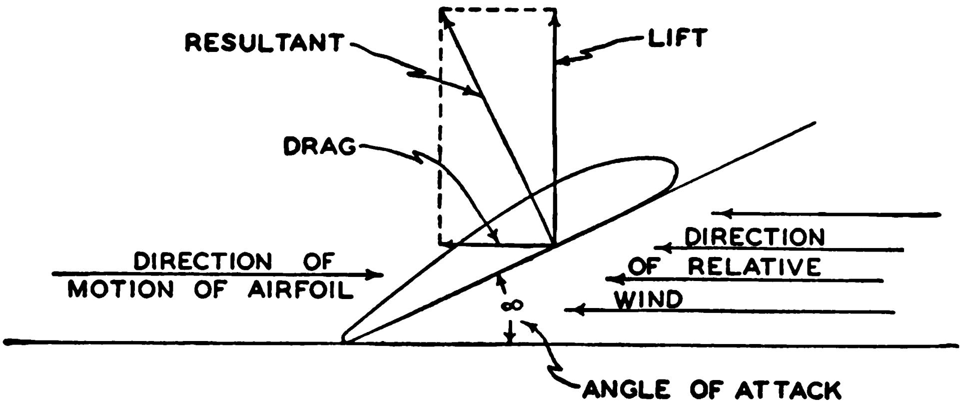


Figure 72.—Aerodynamic forces acting on blade element.

Section V

PROPELLERS

86. General requirements.—In the design and use of aircraft propellers the main consideration is to obtain the maximum performance of the airplane from the horsepower delivered by the engine under all conditions of operation such as take-off, climb, cruising

speed, and high speed. Propellers are classified as the following types:

a. Fixed pitch.—Only one pitch setting due to the type of construction.

b. Adjustable.—Pitch setting adjustable only with tools when the engine is stationary.

c. Controllable.—Pilot can change pitch in flight by manual control.

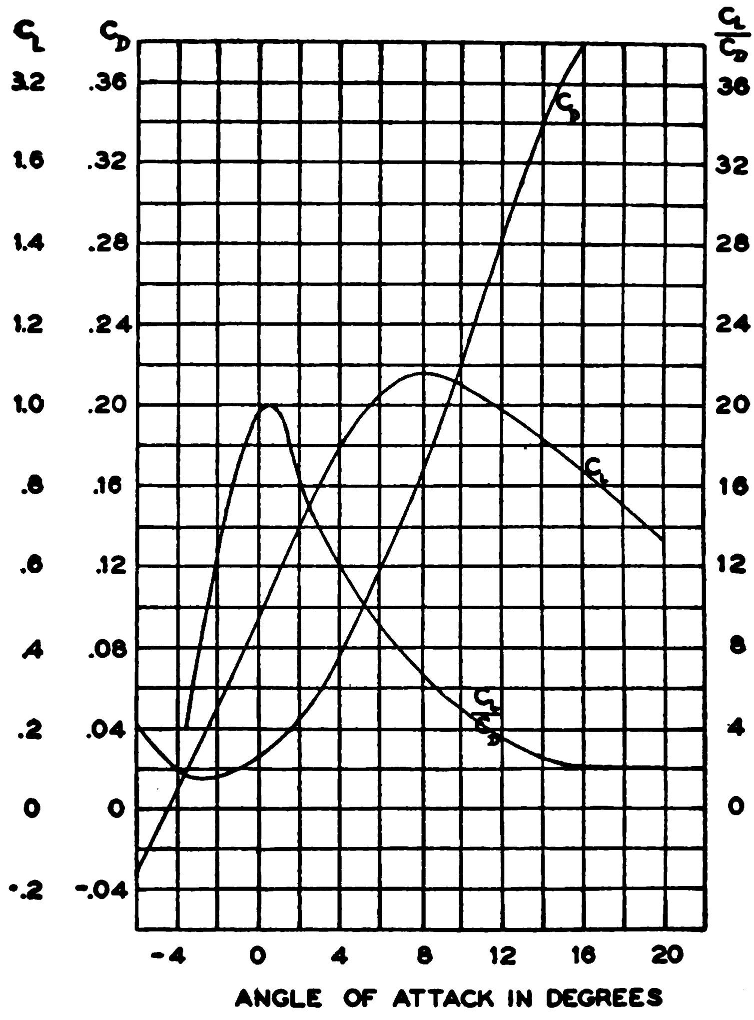


FIGURE 73.—Characteristic curves of blade element.

(1) *Two-position.*—Only two pitch settings available.

(2) *Multiposition.*—Any pitch setting possible within limits.

d. Automatic.—Pitch setting control by some automatic device.

(1) *Nonselective.*—Entirely independent of the pilot.

(2) *Selective.*—Pilot can select and control, during flight, the conditions at which the automatic features function.

The main purpose of the following discussion is to explain the simple aerodynamic characteristics of the propeller under widely varying conditions of operation in such a manner as to show the necessity for controllable or automatic pitch propellers on all present day high performance airplanes.

87. Dryewiecki (Jerveski) or blade element theory.—*a.* The fundamental forces acting on an airfoil in motion with an angle of attack relative to the wind are twofold. A lift force is produced perpendicular to the relative wind and a drag force is produced parallel to the relative wind.

$$L=C_L\rho/2SV_R^2 \qquad (47)$$

The value of the drag force $D=C_D\rho/SV_R^2$ where V_R is the velocity of the relative wind in feet per second. C_L and C_D are the lift and

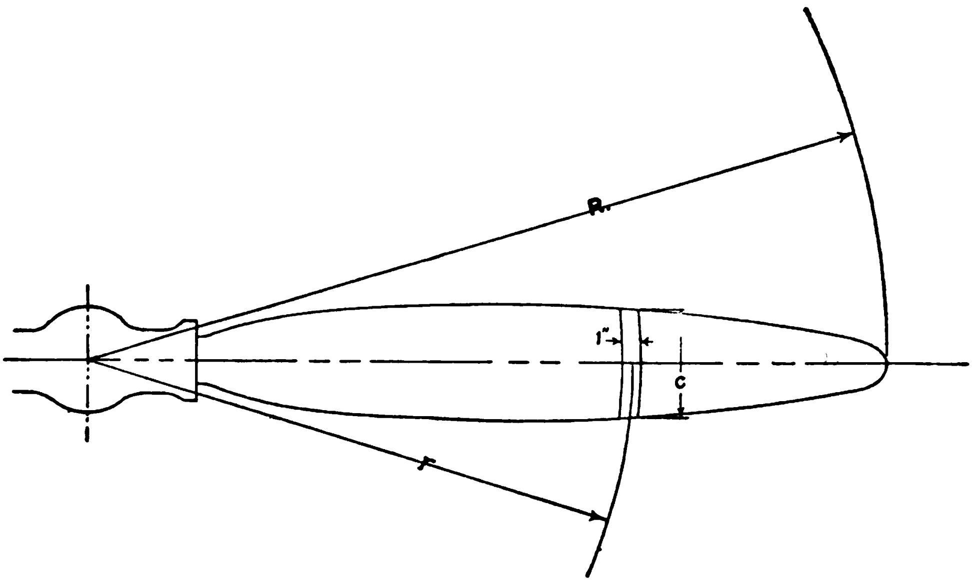


FIGURE 74.—Blade element of propeller.

drag coefficients and their value is dependent upon the shape of the airfoil section, angle of attack, and also upon the velocity relative to the air provided the speed exceeds 700 feet per second. At speeds above the velocity of sound (1,120 ft. per. sec.) the changes in C_L and C_D with changes of velocity are very pronounced.

b. If the airfoil sections are operated above the velocity of sound there is a marked increase in the drag coefficient C_D while the lift coefficient C_L drops. This results in a low L/D ratio and decreased efficiency. When an airfoil section is operated at speeds above the velocity of sound there is a great increase of sound energy produced by the passage of the airfoil through the air. This is very objection-

able for military airplanes since the enemy can easily locate the airplane by the aid of sound locaters.

c. Figure 73 shows the C_L and C_D coefficients for a typical Clark Y section that is commonly used in propeller blades. It can be seen that the most efficient angle of attack α for maximum L/D is about 1°. The characteristic curves shown are for a representative section of a propeller.

d. The blade element theory assumes that the propeller blade from the end of the hub barrel to the tip of the propeller blade is divided into small elementary airfoil sections. For example if a propeller 10 feet in diameter has a hub 12 inches in diameter each blade can be divided into 54 one-inch airfoil sections. Figure 74 shows only one of these airfoil sections located at a radius r from the axis of rotation of the propeller. This airfoil section will then have a span of 1 inch and a chord C. The chord C at any given radius r will depend upon the plan form or general shape of the blade.

88. Propeller blade reactions under various airplane operating conditions.—*a. Static conditions.*—When the airplane is standing still on the ground and the engine is running there are two components of air velocity relative to the blade which determine the blade angle setting. (Fig. 75.)

(1) The speed of the airfoil section in feet per second due to rotation of the propeller is equal to the circumference of a circle having radius r multiplied by the number of revolutions per second. This is equal to $2\pi rn$.

(2) When the propeller is turning there is a stream of air moving at high velocity to the rear of the propeller disk. This stream of air is called the slipstream of the propeller. The air in the slipstream does not gain momentum instantaneously upon striking the propeller blade but gains an appreciable velocity before coming in contact with it. Tests show that the air has gained approximately 31 percent of the velocity of the slipstream by the time it strikes the propeller blade. Since the velocity of the slipstream can be computed, the inflow velocity is obtained by multiplying the slip velocity by 0.31.

b. Take-off and climb condition.—At the time of take-off and during steep climbs the airplane has gained forward speed. (Fig. 76.) There is some decrease in the velocity of the slipstream but the forward velocity of the airplane is sufficient to increase the value of the vector BD. To satisfy this condition of operation the blade angle Θ_B must be greater than for the condition shown in figure 75.

c. Level flight high speed condition.—In level flight at high speed, the forward speed of the airplane has increased to a very high value

while the slip velocity has decreased to a very low value. The sum of $V+0.31V_S$ shown by vector BD (fig. 77) has increased materially over that shown for static conditions and take-off and climb conditions and the angle Θ_B must also be increased.

d. Power dive high speed conditions.—In a power dive the slip velocity is small but the speed of the airplane is so great that the vector BD will be much greater than for any of the above conditions of operation. The blade angle Θ_B will have a very high value.

89. Determination of direction and velocity of airflow relative to propeller blade.—(See fig. 78.) The combination of the velocity due to rotation shown by vector AB and the forward velocity of air relative to the propeller shown by BD can be replaced by the resultant velocity AD. The direction of the airflow relative to

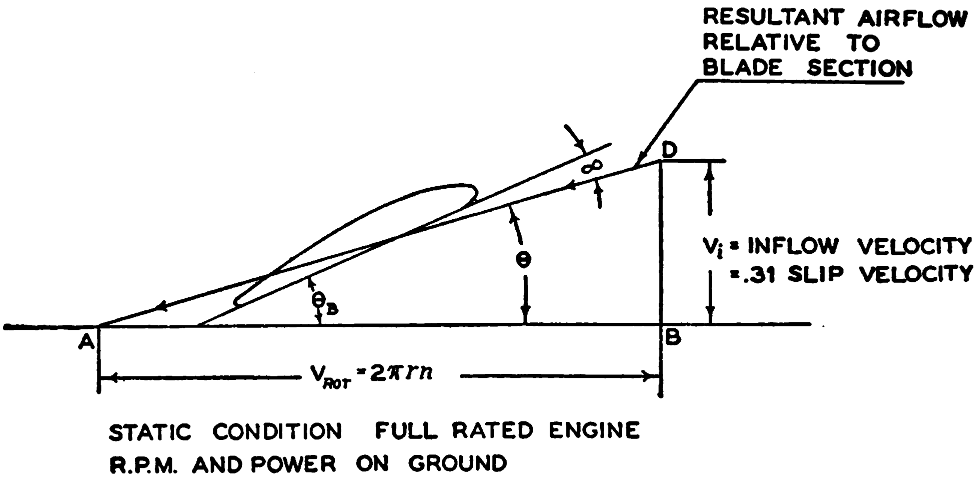
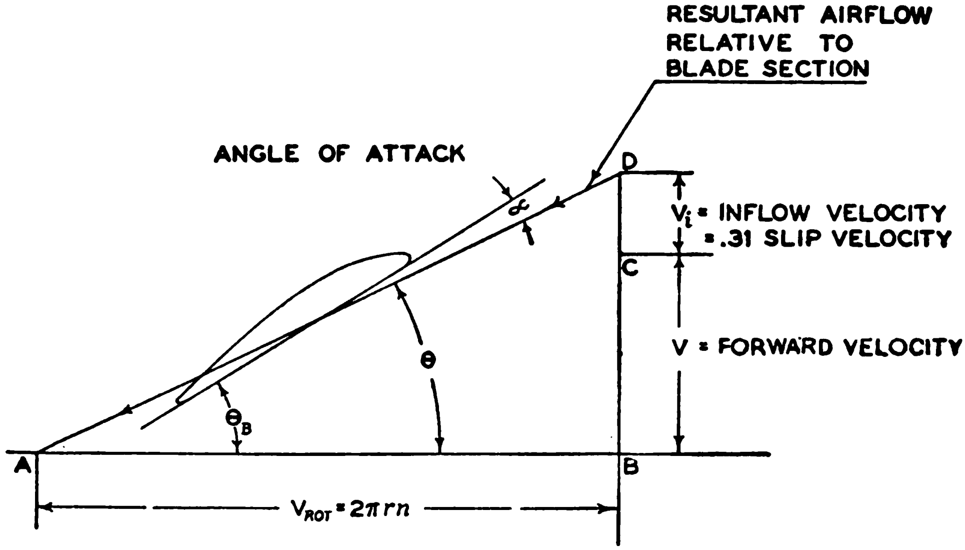


FIGURE 75.—Static condition.

the airplane of rotation is shown by angle Θ which is equal to $\tan^{-1} BD/AB$.

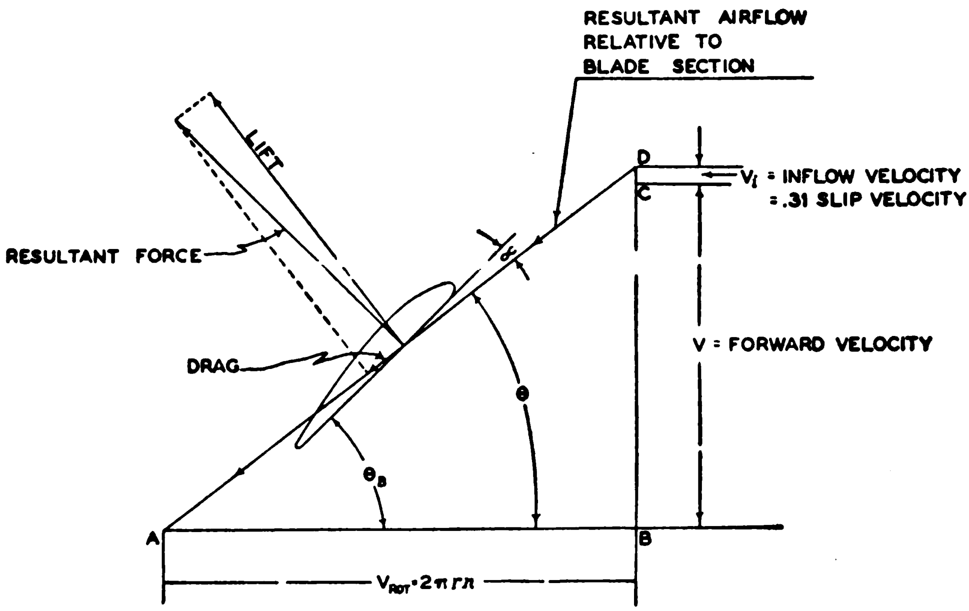
90. Determination of blade angle for airfoil section.—(See fig. 77.) The airfoil section of the propeller will move along the resultant airflow line. The section of the propeller blade is set at an angle of attack α of about 1° so as to obtain maximum L/D which results in maximum efficiency. The angle of the airfoil section with respect to the plane of rotation $\Theta_B=\Theta+\alpha$. The drag on the airfoil section will be parallel to the direction of the resultant airflow and the lift will be perpendicular to the resultant airflow. The lift and drag forces are combined to give the resultant force.

91. Thrust produced by propeller.—In the study of propellers, it is desirable to break down the resultant force into two components, *thrust* and *torque* (fig. 78). The thrust force component is parallel



TAKE OFF AND STEEP CLIMB AT
FULL RATED ENGINE R.P.M. AND POWER

FIGURE 76.—Take-off and steep climb.

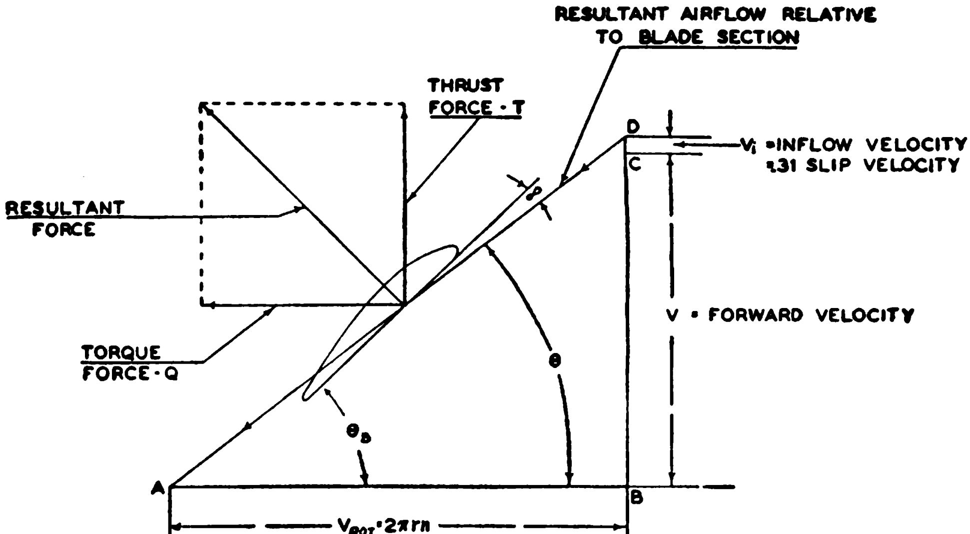


LEVEL FLIGHT HIGH SPEED FULL RATED
R.P.M. AND FULL POWER

FIGURE 77.—Level flight, high speed.

to the axis of rotation of the propeller and is designated by *T*. If *T* is the force in pounds and *V* is the velocity of the airplane in flight in feet per second, the work done per second will be equal to *TV* ft. lbs. per sec. The unit horsepower is equal to 550 ft. lbs. per sec. Therefore $HP=TV/550$=the thrust *HP* produced by the small section of the propeller blade. The thrust horsepower for the complete propeller is obtained by adding together the thrust horsepower produced by all the element airfoil sections of the blades.

92. Torque absorbed by propeller.—The component parallel to the plane of rotation is the torque component force *Q*. The velocity of the elementary airfoil section in the plane of rotation is equal to



RESOLUTION OF RESULTANT FORCE COMPONENTS
OF THRUST FORCE AND TORQUE FORCE

FIGURE 78.—Resolution of resultant force components.

2 π times the radius of the airfoil section from the axis of rotation times the number of revolutions per second.

$$\text{Torque } HP=\frac{Q \times 2\pi rn}{550} \tag{48}$$

The torque *HP* absorbed by the complete propeller is obtained by adding together the torque *HP* absorbed by all the small airfoil sections of the propeller blades. For any speed of rotation the torque *HP* supplied by the engine must balance the *HP* absorbed by the propeller. If the engine torque is greater than the torque required to drive the propeller the engine will increase r. p. m. until a balance is reached. If the torque required to rotate the propeller is

greater than the torque supplied by the engine the engine r. p. m. will decrease until a balance is reached.

93. Fixed pitch propellers.—For the fixed pitch propeller at maximum speed in level flight, a balance is ordinarily reached between the torque horsepower supplied by the engine and the torque horsepower absorbed by the propeller when the engine is turning at its rated speed and delivering its full rated output. In climb, the forward velocity of the airplane decreases, the angle of attack of the relative wind on the propeller blade increases, and the torque horsepower absorbed by the propeller momentarily becomes larger than the horsepower output of the engine. The engine speed then decreases until a new balance is reached between horsepower absorbed by the propeller and the horsepower output of the engine. This decrease in engine speed in climb and the corresponding decrease in horsepower output of the engine result in poor performance in climb of airplanes with fixed pitch propellers.

94. Controllable pitch propellers.—The two-position propeller provides a means of rotating the propeller blades to a reduced pitch angle which permits the engine to turn at normal speed and deliver its full rated horsepower output to the propeller in climb and thus increase the rate of climb. However, this propeller can be designed to give best performance at only two definite speeds of flight. At other speeds in the cruising range and at take-off, performance can be further improved by the use of a propeller whose pitch can be controlled throughout a wide range of pitch angles and which will permit the engine to operate at constant speed in all conditions of flight.

95. Selection of best diameter for propeller.—The diameter of a propeller required to absorb the power output of a given engine is a function of many variables, among which are forward velocity V, air density, speed of rotation of the propeller, number of blades, plan form, profile section, etc. In general, a propeller will only give its best performance for one particular flight condition. The charts shown in figures 79 and 80 are arranged for the convenient selection of suitable diameters for metal controllable pitch propellers of conventional plan form and airfoil section.

Figure 79 is designed to simplify the calculation of C_S, the propeller speed-power coefficient.

$$C_S=\frac{0.638 \text{ m. p. h.}}{HP^{1/5}\,N^{2/5}}\sigma^{1/5} \tag{49}$$

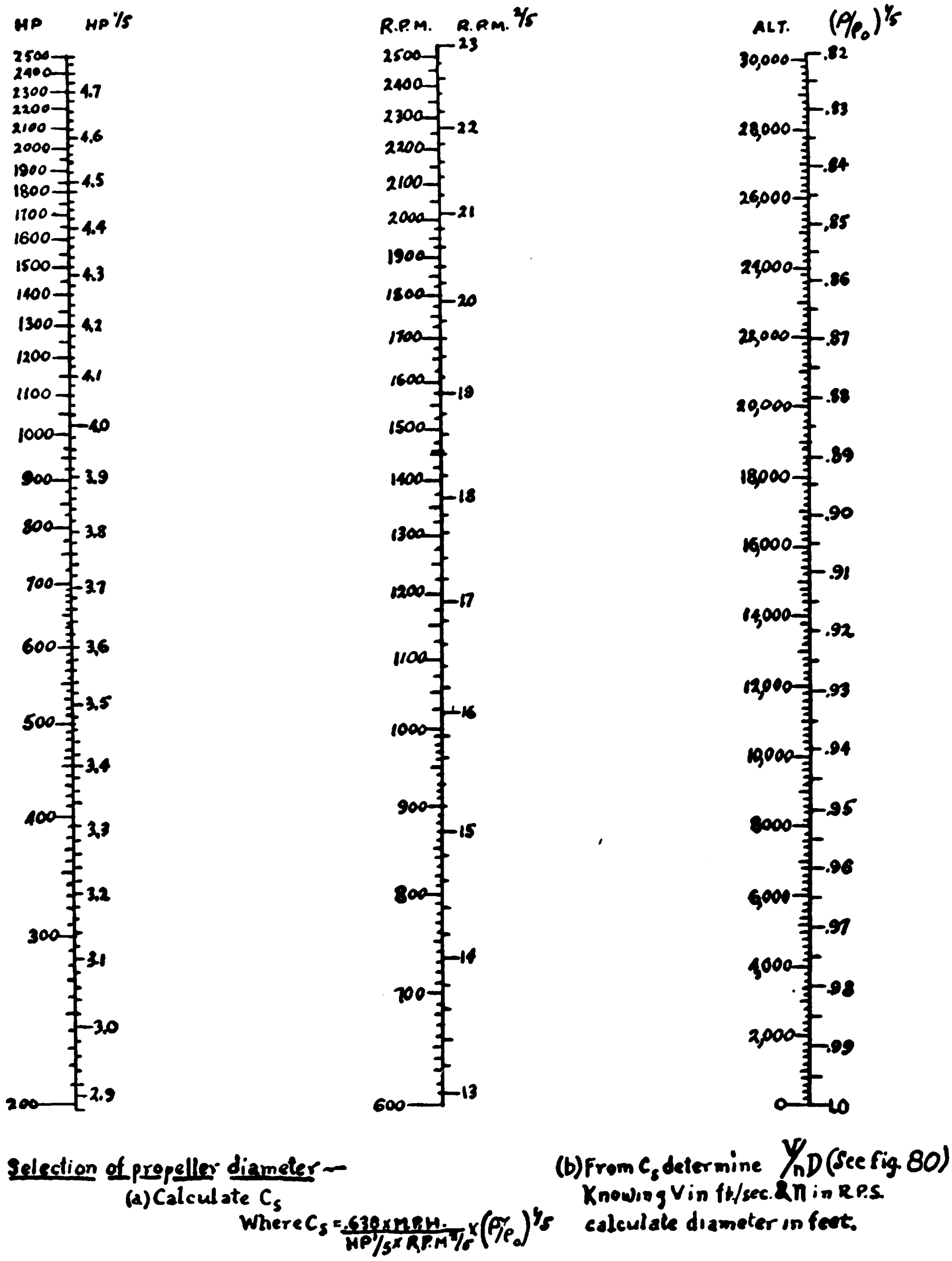


FIGURE 79.—Nomographic chart for solution of C_S.

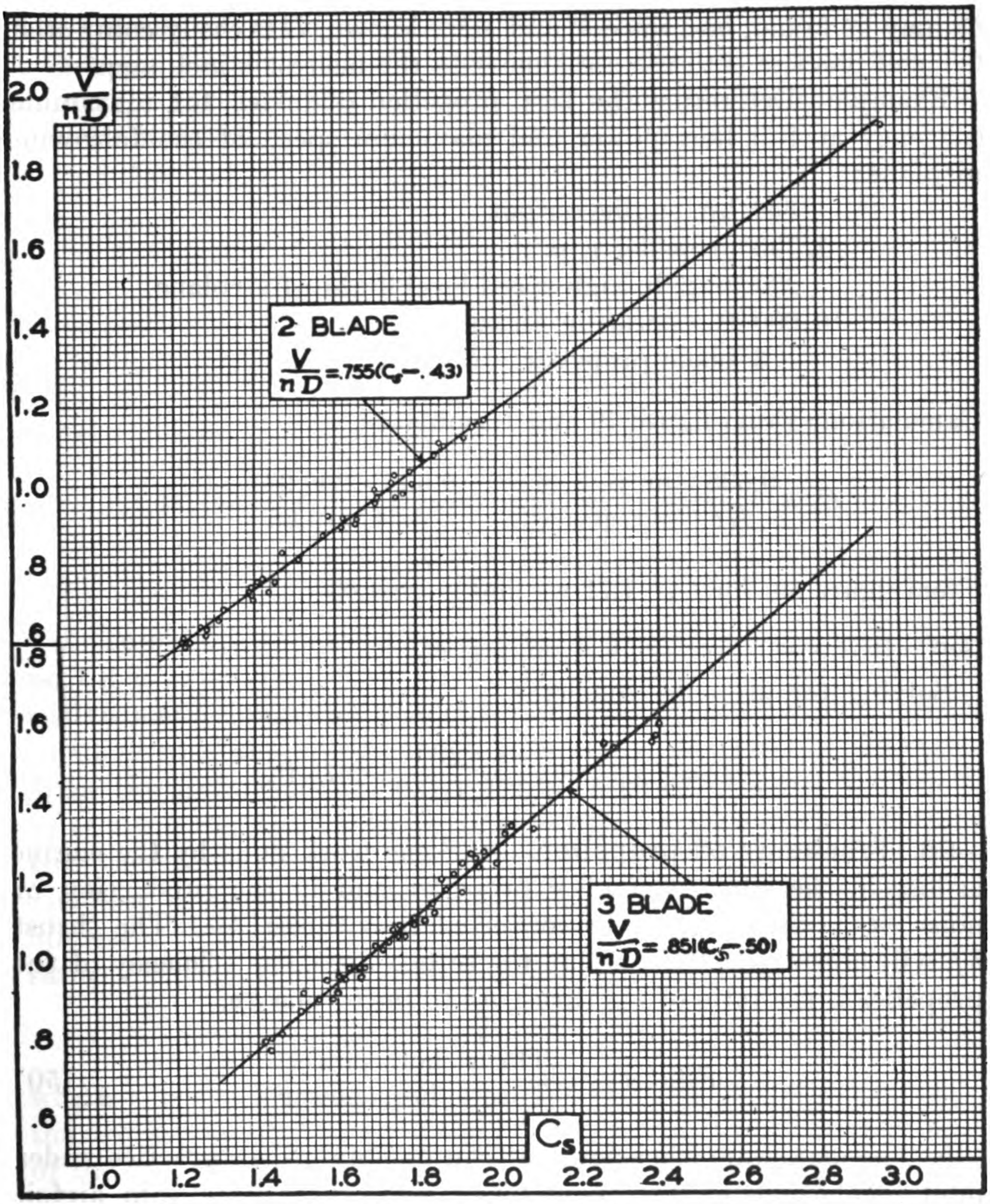


FIGURE 80.—Two- and three-blade C_S–V/nD charts.

where m. p. h. is the forward velocity in miles per hour, HP is the horsepower input to the propeller, N is propeller revolutions per minute, and σ is the density ratio obtained from figure 8.

From figure 80 the $\frac{V}{nD}$ ratio corresponding to the calculated value of C_S may be found, and since V and n are known, D is easily computed. General practise is to use a diameter to the nearest 3-inch step.

Example: Determine the best propeller diameter for maximum efficiency at full horsepower and maximum speed of the following airplane:

550 hp. engine output
1,750 propeller r. p. m.
200 m. p. h. high speed level flight of airplane
10,000 ft. operating altitude
3 blade propeller.

Calculation: From figure 79 and formula 49.

$$C_S=\frac{0.638\times\text{m. p. h.}\times\sigma^{1/5}}{HP^{1/5}\times\text{r. p. m.}^{2/5}}=\frac{0.638\times 200.941}{3.54\times 19.85}=1.71$$

From figure 80, for $C_S=1.71$ we find $\frac{V}{nD}=1.03$

NOTE.—Here V is ft./sec. and n is rev. per sec.

Solving for propeller diameter

$$D=\frac{V}{1.03\ n}=\frac{88\times 200}{1.03\times 1{,}750}=9.75\text{ ft.}$$

96. Efficiency of propeller.—*a.* Some work done by the engine is lost in the slipstream of a propeller and in the production of noise, etc., which cannot be converted into thrust *hp*. The thrust *hp* will necessarily be less than the torque *hp*. The efficiency of the propeller is the ratio of the thrust *hp* to the torque *hp*.

$$\text{Efficiency}=\frac{\text{Thrust horsepower}}{\text{Torque horsepower}} \tag{50}$$

b. The maximum efficiency that can be obtained in practice under most ideal conditions is about 92 percent when using thin airfoil sections near the tip with very sharp leading and trailing edges. Such sections are not practical where there is any danger of picking up gravel or water spray.

c. The efficiency of high performance airplane propellers of conventional two- or three-blade design is dependent mainly upon the

tip speed in feet per second. The following table of efficiencies shows that it is essential to keep the tip velocity below the velocity of sound which is about 1,120 feet per second. The efficiency of high performance airplane propellers of conventional two- or three-blade design is dependent upon the ratio of tip speed to velocity of sound. The velocity of sound varies with temperature and decreases roughly 5 feet per second per 1,000 feet increase in altitude. At sea level it may be taken as about 1,120 ft./sec. The following table of efficiencies is based on a velocity of sound of 1,120 ft./sec.

Tip speed	Maximum efficiency
Feet per second	*Percent*
900	86
950	86
1, 000	85
1, 050	84
1, 100	81
1, 150	77
1, 200	72

d. To obtain tip speeds below the velocity of sound (1,120 ft. per sec.) it is sometimes necessary to gear the engine so that the propeller will turn at a slower rate of speed. For example if an engine is geared in a 3:2 ratio the propeller will turn at 2/3 the speed of the engine. Since the airfoil sections strike the air at a lower speed they do not do as much work as would be the case with the direct drive propeller. It is therefore necessary to increase the blade area by using a larger diameter or three or more blades. The efficiency of a propeller is influenced by the ratio of forward velocity to rotational velocity. This ratio is expressed by a quantity called the V over nD ratio, or

$$V/nD$$

where V is the forward velocity of the airplane in feet per second, n the revolutions per second of the propeller, and D the diameter in feet of the propeller. A particular propeller is designed to give its maximum efficiency at a particular value of forward speed of the airplane (usually the maximum speed in level flight) and a particular engine speed (usually the speed of rated full horsepower output). At any other condition of flight where a different value of the ratio V/nD exists, the propeller efficiency correspondingly suffers.

97. Advantages of three-blade propeller on geared engines.—*a.* The smaller diameter of the three-blade propeller gives lower tip speeds.

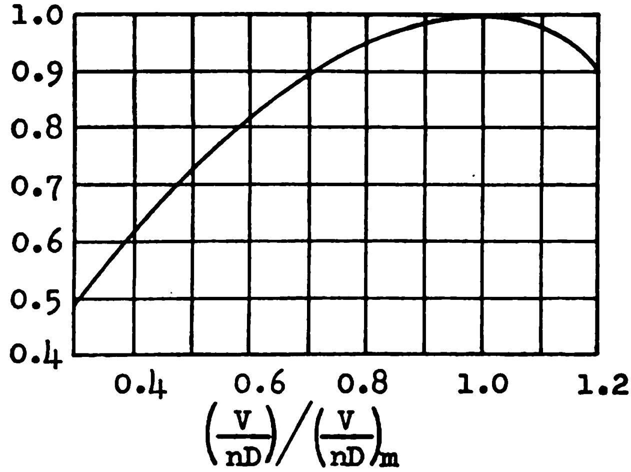


FIGURE 81.—General efficiency curve for fixed pitch propellers.

b. For multi-engined airplanes the engines can be moved in nearer the fuselage which improves maneuverability for flying characteristics with one engine dead. For single-engine airplanes, the smaller diameter gives more ground clearance and allows the use of shorter and lighter landing gears and simplifies the retractable landing gear problem.

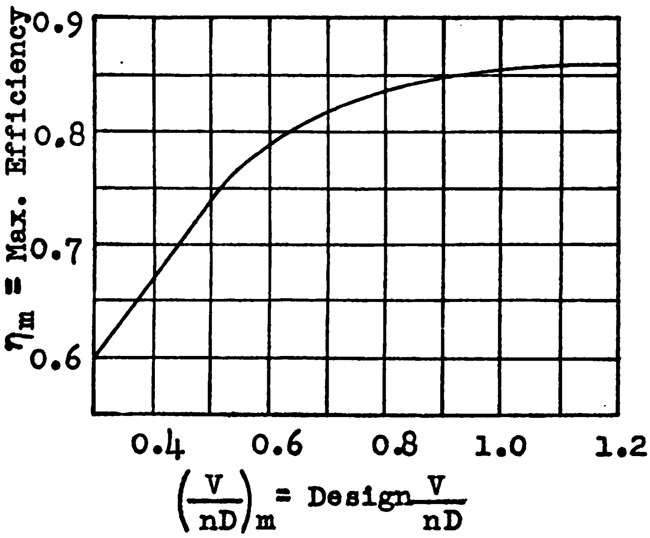


FIGURE 82.—Maximum efficiency of metal propellers for tip speeds less than 950 ft./sec.

c. In the three-blade propeller there is very little interference effect due to the blades being so close together. In the four-blade propel-

ler there is a noticeable loss in efficiency due to the blades interfering with each other.

d. The three-blade propeller prevents the engine from vibrating on the mount to a greater extent than the two-blade propeller. With a two-blade propeller it can be seen that the nose of the engine is not restricted to any great extent from movement at right angles to the axis of the propeller blades. For example if the blades are horizontal the nose of the engine can jump up and down vertically more easily than horizontally. The three-bladed propeller acts more as a flywheel and tends to prevent movement of the nose of the engine in any direction.

98. Computations of blade angles.—*a.* When adjusting the blade angles of a propeller to meet different flight requirements a definite station on the blade is selected and the angle of attack with respect to the plane of rotation is computed for the station selected. For propellers up to 12 feet in diameter the 42-inch station is selected as a reference station for setting the blades. For propellers between 12 feet and 17 feet in diameter the 54-inch station is selected.

b. If the total disk area of a propeller were effective, the disk area would be equal to $\pi D^2/4=0.785D^2$. Since the part of the disk area near the center of the propeller is blanked out by the propeller hub, it is considered that the effective area of the propeller disk

$$A_S=0.065D^2 \tag{51}$$

D is expressed in feet.
A_S is expressed in square feet.

c. The velocity of the slipstream to the rear of the propeller is computed by the following formula:

$$V_S=\frac{HP\times 550\times \eta}{\sigma\times 0.00238\times V^2\times A_S} \tag{52}$$

where $HP=HP$ output of the engine and η is determined approximately from paragraph 96.

d. σ is the relative density of the air at the altitude at which the airplane will fly and is obtained from relative density curves (fig. 8). V is the velocity in feet per second at which the airplane will fly with HP being developed by the engine.

The tangent of the angle $\Theta=\frac{BD}{AB}$ (refer to fig. 77)

$$\text{Tan } \theta=\frac{V+.31V_S.}{2\pi\ rn} \tag{53}$$

The blade angle relative to the plane of rotation $\Theta_B=\theta+\alpha$.

Example: Compute the blade angle setting at the 42-inch station for the following airplane engine and propeller combination. Airplane air speed at 15,000 ft.=280 m. p. h.=410 ft./sec.

Engine 1,000 HP at 15,000 ft. altitude at 2,200 r. p. m.
Engine geared with a 3/2 ratio.
From figure 8, σ at 15,000 ft.=0.625.
Propeller 3-blade, diam. 12 ft. 6 in.
Propeller (geared) r. p. m.=$\frac{2}{3}\times 2{,}200=1{,}466$ r. p. m.=24.44 r. p. s.
Rotational velocity of propeller tip=$2\pi\times 6.25\times 24.44=960$ ft./sec.
Component of tip speed due to advance of the airplane=410 ft. per sec.
Resultant tip speed=$\sqrt{(960)^2+(410)^2}=1{,}043$ ft. per sec.
Assume an efficiency of 84 percent for the propeller from paragraph 96.
From formula 50

$$A_S=0.605\times(12.5)^2=94.5 \text{ sq. ft.} \tag{54}$$

The most effective angle of attack α for the section is 1°.
(Refer to fig. 73)
Substituting these values in formulas 51 and 52, we obtain the required blade angle setting at the 42-inch station.

$$V_S=\frac{1{,}000\times 550\times 0.84}{0.625\times 0.00238\times(410)^2\times 94.5}=19.6 \text{ f. p. s.} \tag{55}$$

NOTE.—The slip velocity is very small for the high speed condition of flight. The slip values will be much higher for conditions of take-off, climb, and cruising.

$$\text{Tan } \theta=\frac{410+(0.31\times 19.6)}{2\times 3.5\times 24.44}=\frac{416}{540}=0.77 \tag{56}$$

$$\begin{aligned} \text{Tan}^{-1}&=0.77=37.6°=\theta \\ \theta&=37.6° \\ \alpha&=\ \ 1° \\ \hline \theta_B&=38.6°, \text{ the blade angle setting at 42-inch station.} \end{aligned} \tag{57}$$

Slight changes of blade angle can be made if the engine does not run exactly at rated speed. For a direct drive propeller a blade angle change of 1° will change the engine speed approximately 70 r. p. m. on the ground and 100 r. p. m. in level flight at wide open throttle. For geared engines the change of engine r. p. m. will be greater and will vary directly with the ratio of gearing.

99. Advantages of controllable pitch propellers.—In paragraph 101 is shown performance data indicating the wide variation of angles required for a modern 4-engine airplane with engines supercharged to 15,000 feet if maximum performance under all operating conditions is to be maintained. If it were necessary to use a fixed pitch propeller for this airplane, the best blade setting would be about 38.6° at the 42-inch station.

a. Improved climb and take-off.—The best condition for take-off would require a blade angle of 16° if it is desired to use 100 percent of rated power for take-off. With a fixed pitch propeller set at 38.6° the angle of attack relative to the airfoil would be at least $38.6° - 18° = 20.6°$. By referring to the lift and drag curves (fig. 74), it can be seen that the drag would be very high which means that the torque required to drive the propeller would be much greater than the torque supplied by the engine. This will result in the engine slowing down until a balance of power supplied by the engine and power absorbed by the propeller is reached. In the above case the engine would slow down to about one-half of its rated speed and the power output would be about one-half of full rated power. The 50 percent power that is being absorbed by the propeller is being consumed very inefficiently, as the L/D of the airfoil section is very low and the thrust from the propeller will be low. By the proper adjustment of the blade angle for take-off and climb, full engine power can be used with more efficient blade angles of attack so that the airplane will take off in about one-third the distance and climb about twice as fast as with the fixed pitch propeller with a blade angle setting at 38.6°.

b. Improved high speed at sea level.—If a blade angle of 38.6° is used for high speed at altitude (15,000) the angle of attack at sea level will be $38.6° - 32.4° = 6.2°$. This high angle of attack will result in the speed of the engine being held down until only 80 percent of the rated power can be obtained from the engine. This will result in a loss of 20 m. p. h. in high speed at sea level.

c. Improved fuel economy at cruising speeds.—By adjusting the pitch angle of the propeller and the throttle so as to cruise at the maximum allowable intake manifold pressure a saving of approximately 7 percent in fuel can be realized. Maximum allowable manifold pressure is the intake manifold pressure that will force the largest charge of fuel and air mixture into the cylinder that will burn without detonation or preignition. When the engine is operating under high manifold pressures, greater thermal efficiencies are attained. The lower engine r. p. m. also results in less loss of power due to friction of the moving parts of the engine. If the propeller

is to absorb more power at a slower r. p. m., the blade angle must be increased to a value greater than the setting required for high speed. It will be noticed that when cruising with increased propeller pitch and high manifold pressure more throttle opening will be required than is required for cruising with a fixed pitch propeller set for high speed conditions.

d. Increased performance with part of engine plant shut down.—For long range military aircraft about half of the flying will be done under light conditions of load since the bomb load and part of the fuel supply will be disposed of. Fuel economy can be obtained by shutting down two engines as shown in paragraph 101 and feathering the blade on the dead engines. The blades are feathered by increasing the blade angle at the 42-inch station to approximately 87° so that the blade has a very low angle of attack. The drag will be much less than if the propeller were stopped by brakes with the blades set at angles required for flight. It is estimated that about 12 miles an hour could be gained on this airplane by feathering the blades instead of keeping the propellers from windmilling by the use of brakes.

e. Increased ceiling.—When a supercharged engine has passed its rated altitude the power will start to decrease due to the decrease in intake manifold pressure. This results in a decrease in engine speed. The supercharger speed will drop which in turn lowers the manifold pressure, the cycle repeating itself. The ceiling can be materially increased with a controllable pitch propeller by decreasing the blade angle so that the engine will run up to its rated speed which maintains the speed of the supercharger at normal and prevents the manifold pressure and power of the engine from dropping off as rapidly as would be the case with a fixed pitch propeller.

100. Advantages of constant speed propeller.—Reference to paragraph 101 will show that to obtain best conditions of operation the pilot will have somewhat of a problem to select the proper pitch setting. It is also annoying to have to change the pitch to meet all requirements. The constant speed propeller has been developed to select automatically the proper pitch angle for the blades and relieve the pilot of manually changing the pitch setting. The propeller pitch is changed to maintain automatically any desired engine speed. The pilot merely sets the propeller control at the r. p. m. at which it is desired to operate. The throttle is then opened until the desired manifold pressure is obtained. The airplane may then be flown through all types of maneuvers without a change of engine speed of more than 10 or 20 revolutions a minute. If the constant speed

propeller control is set to obtain full rated engine r. p. m. the following pitch changes will occur to maintain constant engine speed:

a. At the start of the take-off the pitch will be low to allow the engine to turn at full rated r. p. m. and develop full power.

b. Throughout the take-off and climb the pitch will gradually increase as the speed of the airplane increases so that full engine power will be delivered throughout take-off and climb.

c. As the airplane is leveled off after the climb, the speed of the airplane increases and the pitch automatically increases to prevent racing of the engine and to maintain constant engine speed.

d. In a dive the pitch angle increases to a still higher value to maintain constant engine r. p. m.

e. For cruising conditions the constant speed control is set at the desired r. p. m. required for cruising. The propeller then automatically regulates the pitch to maintain the selected cruising r. p. m. of the engine. The throttle is adjusted to give the desired manifold pressure.

f. When the throttle is closed the speed of the airplane decreases and the pitch automatically decreases. Low and high pitch stops are usually provided to prevent the propeller from attaining blade angle settings that are too low or too high for flight conditions.

101. Comparison of performance of modern four-engine monoplane at sea level and at 15,000 feet.—Engines: 1,000 hp. each at 2,200 r. p. m. All engines equipped with controllable pitch propellers.

a. At sea level:

Cruising speed, 204 m. p. h. with blade angle of 41.7° 70 percent max. HP at 1,400 r. p. m.

High speed, 230 m. p. h. with blade angle of 32.4°.

Cruising speed with 2 propellers feathered 170 m. p. h. 80 percent max. HP at 1,700 r. p. m. and blade angle of 32.8°.

b. At 15,000 feet:

Cruising speed, 248 m. p. h. with blade angle of 47.4° 70 percent max. HP at 1,400 r. p. m.

High speed 280 m. p. h. with blade angle of 37.7°.

Cruising speed with 2 propellers feathered 206 m. p. h. 80 percent max. HP at 1,700 r. p. m. and blade angle of 38°.

Best climbing speed 160 m. p. h. with blade angle of 26°.

SECTION VI

PERFORMANCE

102. Definition.—The term "performance" is broad enough to include all the characteristics of an airplane in flight. Ordinarily, however, the term is used in a restricted sense to include only those flight qualities directly measurable quantitatively such as speed, rate of climb, etc. Those qualities such as stability, controllability, etc. which are not readily measured in figures are not included in performance as thus defined. The performance characteristics are summarized as follows:

a. Maximum speed in level flight at any altitude.
b. Rate of climb at any altitude.
c. Time of climb to various altitudes.
d. Ceiling, the maximum altitude attainable.
e. Endurance, the maximum duration of flight.
f. Range, the maximum flight distance.
g. Landing speed.
h. Length of roll on landing.
i. Length of roll on take-off.

103. Work and power.—Where the action of a force on a body produces motion, the amount of work done is the product of the force times the distance through which the body moves along the line of action of the force.

$$\text{Work (ft. lbs.)} = \text{Force (lbs.)} \times \text{distance (feet)}$$

Power is the rate at which work is done.

$$\text{Power (ft. lbs./sec.)} = \frac{\text{Work (ft. lbs.)}}{\text{Time (sec.)}}$$

The unit of power commonly employed is the horsepower.

$$1\ HP = 550 \text{ ft. lbs./sec.}$$

104. Performance calculations.—In making calculations of performance, many simplifying assumptions are customarily made to reduce the tremendous labor involved in making exact calculations. These assumptions are justified on the ground that the errors involved are so small as to warrant neglecting them. The assumptions made are—

a. The motion in flight is unaccelerated.

b. The thrust of the propeller acts in a horizontal direction and is equal to the total drag of the airplane.

c. The lift of the wings is constant and equal to the total weight of the airplane.

d. The lift forces on the fuselage and tail assembly are so small that they may be neglected.

In the further discussion of performance, the foregoing assumptions will be considered in effect without further reference to them.

105. Power required at sea level.—By definition,

$$\text{Power} = \text{force (drag)} \times \frac{\text{distance}}{\text{time}} \text{(velocity)}$$

The power required for level flight, P_r is the sum of the power required to pull the wings through the air plus the power required to overcome the parasite resistance.

$$P_r = P_{\text{wings}} + P_{\text{parasite}} \qquad (58)$$

$$= VD_{\text{wings}} + VD_{\text{parasite}} \qquad (59)$$

For any assumed value of V, the corresponding wing drag and parasite drag may be determined and the power required calculated from equation 59. The power required may be calculated for a number of different airspeeds and a curve plotted of power required against airspeed. Since we are accustomed to think in mile per hour units rather than in feet per second units, the curve is usually plotted against airspeed in miles per hour (fig. 83).

In determining the wing drag, wind tunnel test data on the airfoil section concerned must be available, and since these data are plotted against C_L, it is necessary to determine C_L at the speed of flight from the characteristics of the airplane.

Example: Monoplane wing cellule (60)

$W = 6{,}000$ lbs.
$S = 300$ sq. ft.
$b = 45$ ft.
$AR = b^2/S = 6.75$
$A_e =$ (at high speed) $= 5$ sq. ft.
Airfoil section—N. A. C. A. 2218–09

Required: C_L at 140 miles per hour at sea level

Solution: 140 m. p. h. = 205 ft./sec.

$$C_L = \frac{W}{\rho/2SV^2} \tag{61}$$

$$= \frac{6{,}000}{\frac{0.00238}{2} \times 300 \times 205 \times 205} = 0.398$$

Required: Power required by the wings at 140 m. p. h. at sea level.

Solution: From the aerodynamic data on the profile section N. A. C. A. 2218–09 (fig. 46) when $C_L = 0.398$,

$$C_{D_o} = 0.0100 \tag{62}$$

$$C_D = C_{D_o} + \frac{C_L^2}{\pi AR}$$

$$= 0.0100 + \frac{0.398 \times 0.398}{3.14 \times 6.75} = 0.0175 \tag{63}$$

Wing drag $D = C_D \rho/2SV^2 = 0.0175 \times \frac{0.00238}{2} \times 300 \times 205 \times 205$

$$= 263 \text{ lbs.} \tag{64}$$

Power required by the wings

$$= HP_{\text{wings}} = \frac{D \times V}{550} = \frac{263 \times 205}{550} = 98HP \tag{65}$$

Required: Power required by the parasite resistance at 140 m. p. h. at sea level.

Solution:

$$D_P = 0.00152 A_e V^2 = 0.00152 \times 5 \times 205 \times 205 = 320 \text{ lbs.} \tag{66}$$

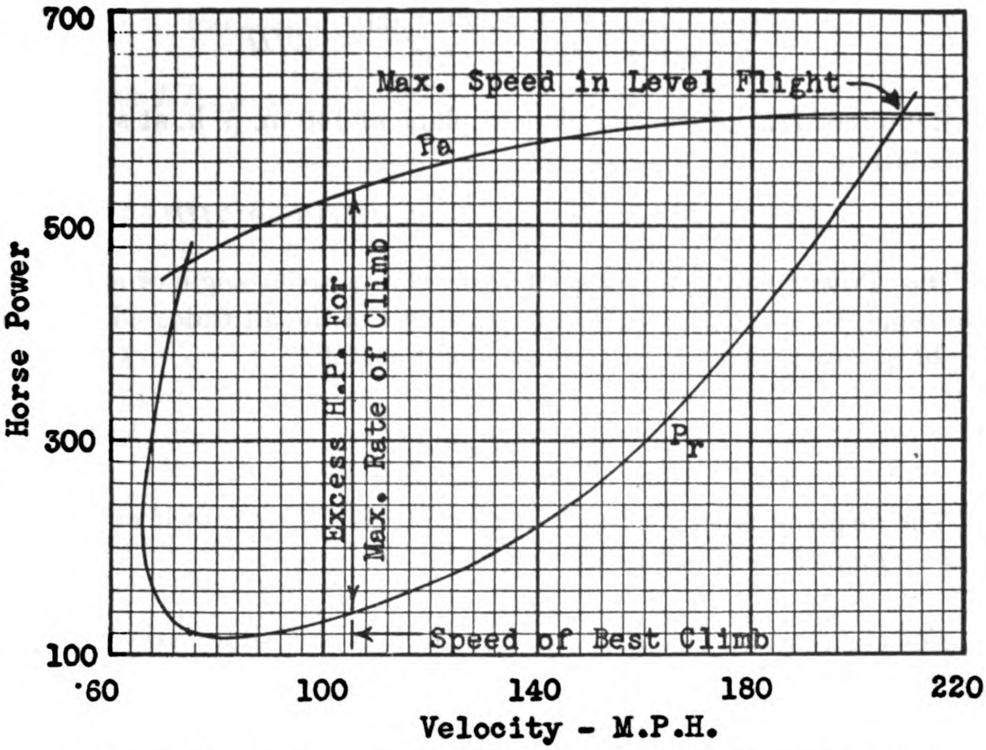


FIGURE 83.—Horsepower required and horsepower available for a typical airplane at sea level.

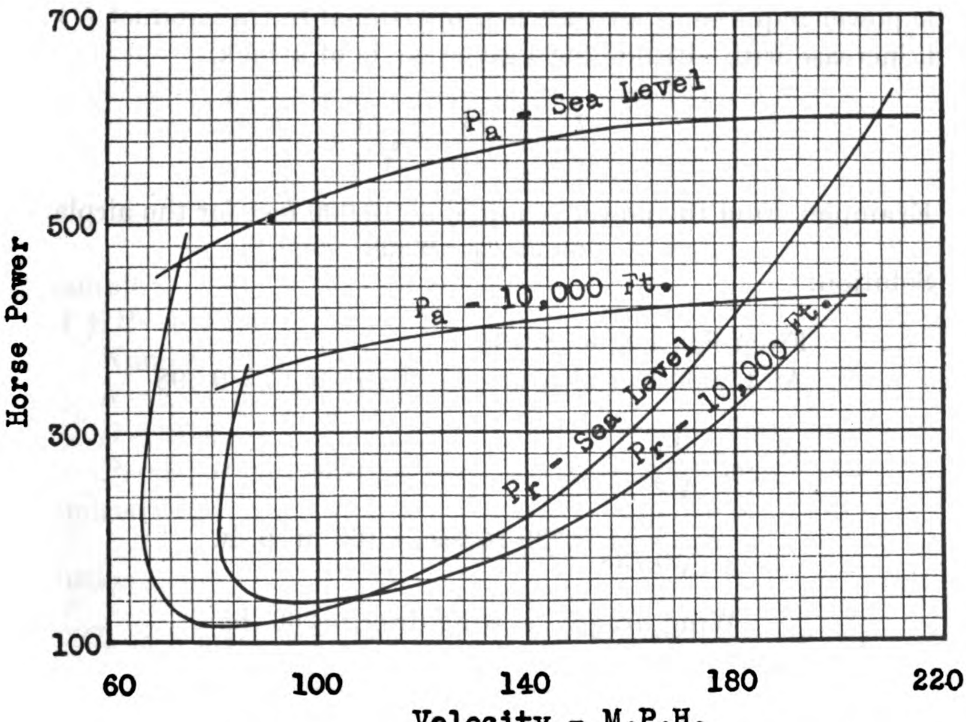


FIGURE 84.—Horsepower required and horsepower available for a typical airplane.

$$HP_{\text{parasite}}=\frac{D_P V}{550}=\frac{320\times 205}{550}=119HP \tag{67}$$

Required: HP_r of the complete airplane at 140 m. p. h. at sea level.
Solution:

$$HP_r=HP_{\text{wings}}+HP_{\text{parasite}}=98.0+119=217HP \tag{68}$$

106. Power required at altitude.—For a given angle of attack of the wing, C_L and C_D are constant regardless of the altitude. For level flight at any altitude at a given angle of attack.

$$\frac{V}{V_o}=\sqrt{\rho_o/\rho}=\sqrt{\frac{1}{\sigma}} \tag{69}$$

The airplane must fly faster at altitude to support itself at a given *angle of attack* because the density of the air is less.

For a given *angle of attack*, $\frac{V^2}{V_0^2}$ increases in the same ratio that ρ/ρ_o is reduced, so that the drag at altitude is the same as at sea level.

$$D=D_o \text{ for constant angle of attack} \tag{70}$$

The power required at altitude is proportional to the product DV and will increase with altitude for a given angle of attack.

$$\frac{P_r}{P_{ro}}=\frac{DV}{D_oV_o}=\sqrt{\frac{1}{\sigma}} \tag{71}$$

Example: Find the power required at 10,000 feet for the airplane of 60 at $C_L=0.398$

Solution:

From figure 8, $\sigma=0.738$
At 10,000 feet altitude, for flight at $C_L=0.398$

$$V_{10,000}=\frac{V_o}{\sqrt{\sigma}} \tag{72}$$

$$=\frac{205}{\sqrt{0.738}}=239 \text{ ft./sec.}=163 \text{ m. p. h.}$$

$$\text{Wing drag}_{10,000}=\text{wing drag}_o=263 \text{ lbs.} \tag{73}$$

$$\text{Wing } HP_{10,000}=\frac{\text{wing drag}_o\times V_{10,000}}{550}=\frac{263\times 239}{550}=114\ HP \tag{74}$$

$$\text{Parasite drag}_{10,000}=\text{parasite drag}_o=330 \text{ lbs.} \quad (75)$$

$$\text{Parasite } HP_{10,000}=\frac{\text{parasite drag}_o \times V_{10,000}}{550}=\frac{320\times 239}{550}=139\ HP \quad (76)$$

$$HP_{r10,000}=114+139=253\ HP \quad (77)$$

The curves of horsepower required in figure 84 are obtained by the tabulation and calculation of a large number of points of *HP* required for different airspeeds and altitudes. The general shape of the power required curve is similar for all airplanes.

107. Power available at sea level.—The power output at full throttle of an engine at sea level is nearly proportional to the engine speed. With a fixed pitch propeller, the engine speed is less and its power output correspondingly less at climbing speeds than in level flight at full speed. With controllable pitch propellers the engine speed may be kept constant, and its power output constant throughout the flight range.

The power available is equal to the engine power multiplied by the propeller efficiency. The propeller efficiency is a function of several variables, and may best be determined by the use of graphical curves for the type of metal propellers now in service (fig. 85).

C_P is defined as the power coefficient of the propeller and is expressed by the equation

$$C_P=\frac{P\times 10^{11}}{BN^3D^5\sigma}, \text{ where} \quad (78)$$

P=Power output of the engine
B=number of blades
N=r. p. m. of the propeller
D=diameter in feet
σ=density ratio at altitude of flight

Example:
Rated HP=P=700 (79)
Number of blades=B=3
N=r. p. m. of propeller=1,650
D=10 ft.
Propeller controllable, constant speed σ=1 at sea level

Required:
C_P at sea level

Solution:

$$C_P \text{ (sea level)}=\frac{700\times 10^{11}}{3\times 1,650\times 1,650\times 1,650\times 10^5\times 1}=0.052 \quad (80)$$

Required: Propeller efficiency at 140 m. p. h.
Solution: 140 m. p. h.=205 ft./sec.

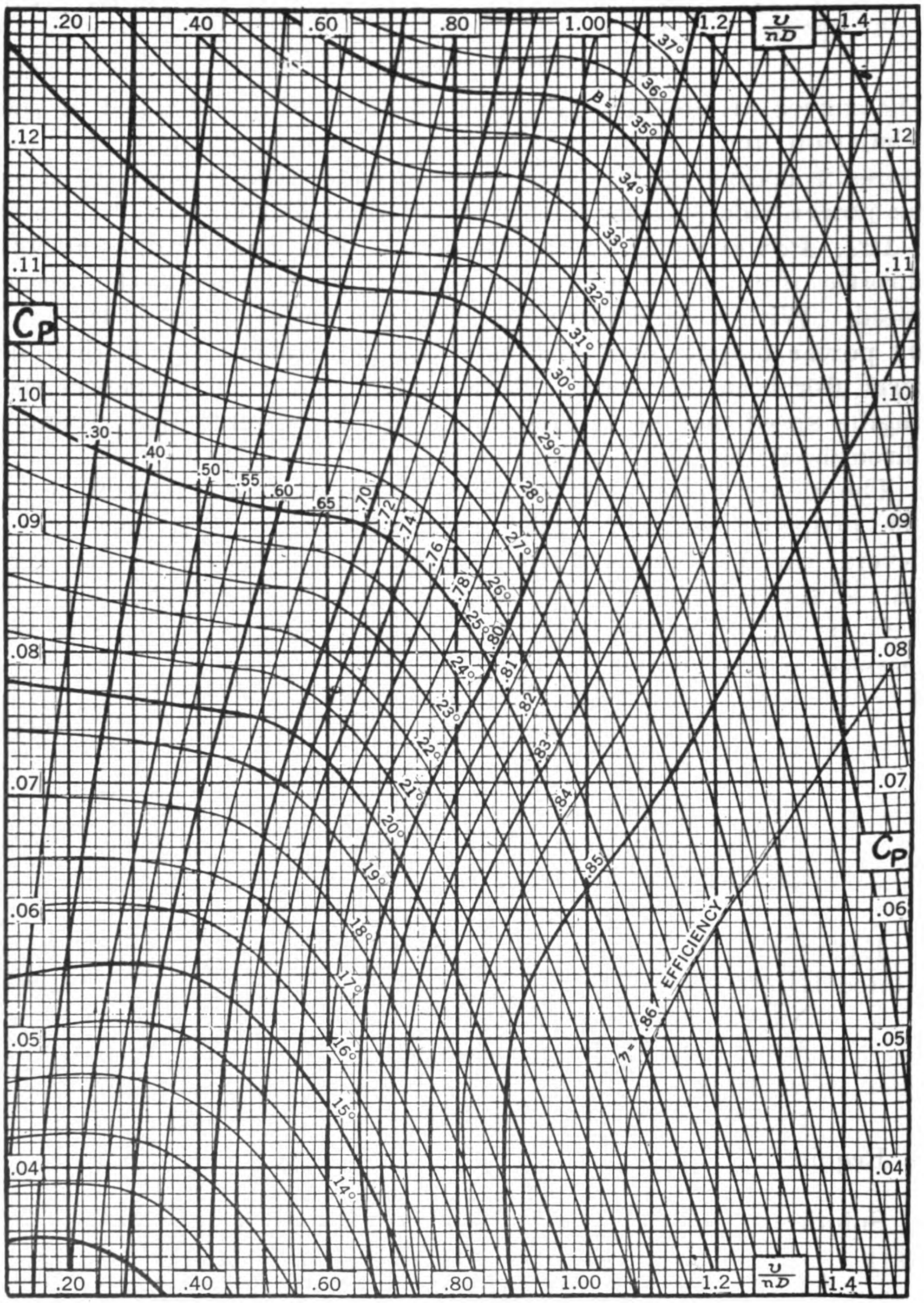


FIGURE 85.—Propeller characteristics.

$$\frac{V}{nD}=\frac{205\times60}{1{,}650\times10}=0.747 \tag{81}$$

From the chart of propeller characteristics figure 85.

Required: $\eta=0.824$

$$\begin{aligned} &P_a \text{ at 140 m. p. h.} \\ &HP \text{ output of engine}=700\ HP \\ &P_a=\eta\times700 \\ &\quad=0.824\times700=577\ HP \end{aligned} \tag{82}$$

For other assumed airspeeds, P_a may be computed and the curve plotted for the entire range of flight speeds (fig. 83).

108. Power available at altitude.—At altitude the indicated power output of the airplane engine at a given r. p. m. decreases in direct proportion to the decrease in density ratio, unless by supercharging the power output is boosted. With fixed pitch propellers, the unsupercharged engine loses speed with increase in altitude, the net result being further decrease in power output due to decreased r. p. m.

Example: Supercharged engine, critical altitude 10,000 feet.

Required: P_a at 10,000 feet at 140 m. p. h.

Solution: From formula 80, C_P at sea level$=0.052=C_{P_0}$

$$\begin{aligned} C_{P10{,}000}&=C_{P_0}/\sigma \\ &=\frac{0.052}{0.738}=0.0705 \end{aligned} \tag{83}$$

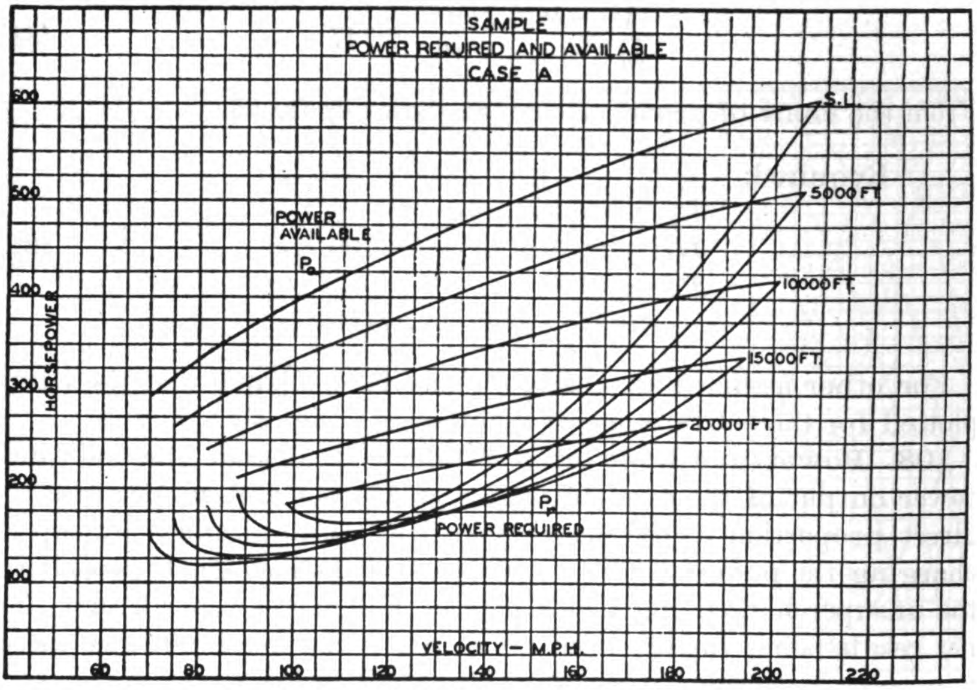
For a constant speed propeller at $V=140$ m. p. h.

$$\frac{V}{nD}=0.747 \text{ (from formula 81) from figure 85 } \eta=0.794 \tag{84}$$

$$\begin{aligned} P_{a10{,}000}&=\eta\times HP \text{ output of engine} \\ &=0.794\times700 \\ &=556\ HP \end{aligned} \tag{85}$$

For other assumed airspeeds, P_a may be computed and the curve plotted at altitude in the same manner as at sea level.

109. Maximum speed in level flight.—The curves of P_r and P_a for any particular altitude of flight intersect at two points which define the minimum and maximum speeds respectively in level flight. The maximum speed is the characteristic which is of prime importance in performance. For airplanes with unsupercharged engines, the maximum speed in level flight decreases with altitude. For airplanes with supercharged engines, the maximum speed in



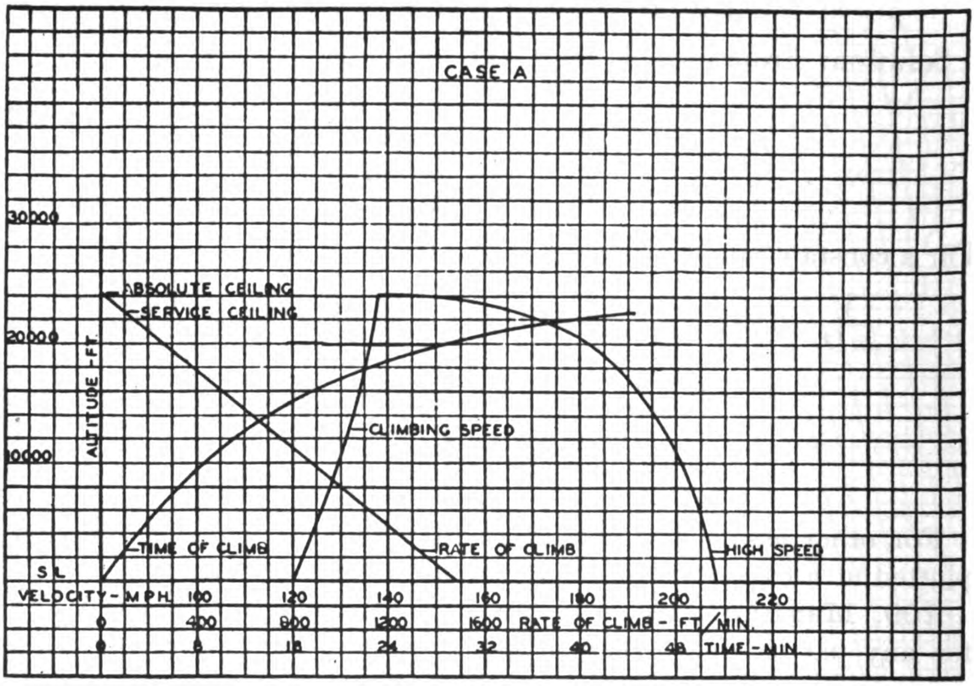


FIGURE 86.—Performance characteristics of a monoplane with 3-blade adjustable, 10-foot propeller; unsupercharged 700 HP engine at 1,650 r. p. m. propeller speed; weight 6,000 pounds; wing area 300 square feet; span 45 feet; A. R. 6.75; airfoil section N. C. A. C. 2218-09.

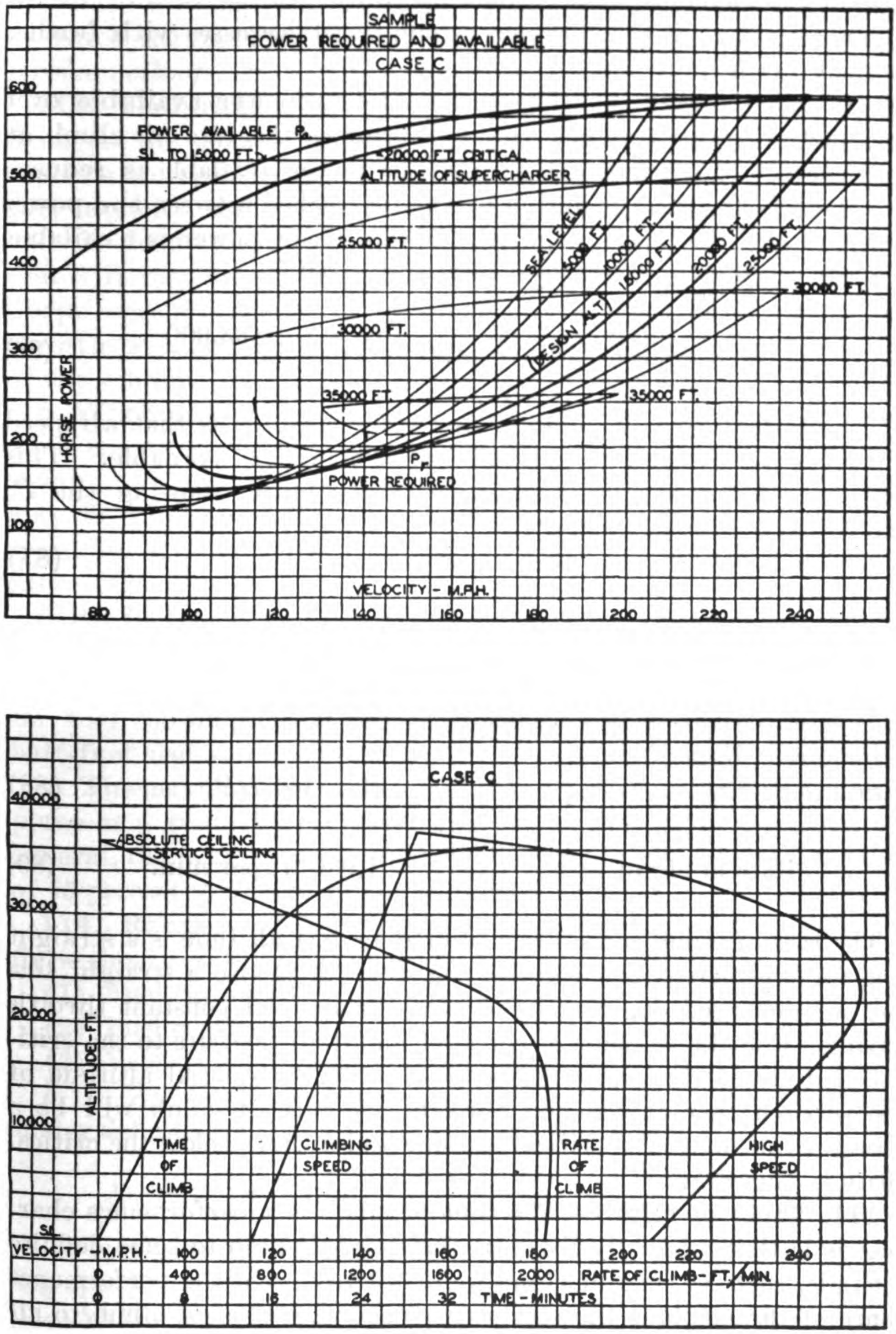
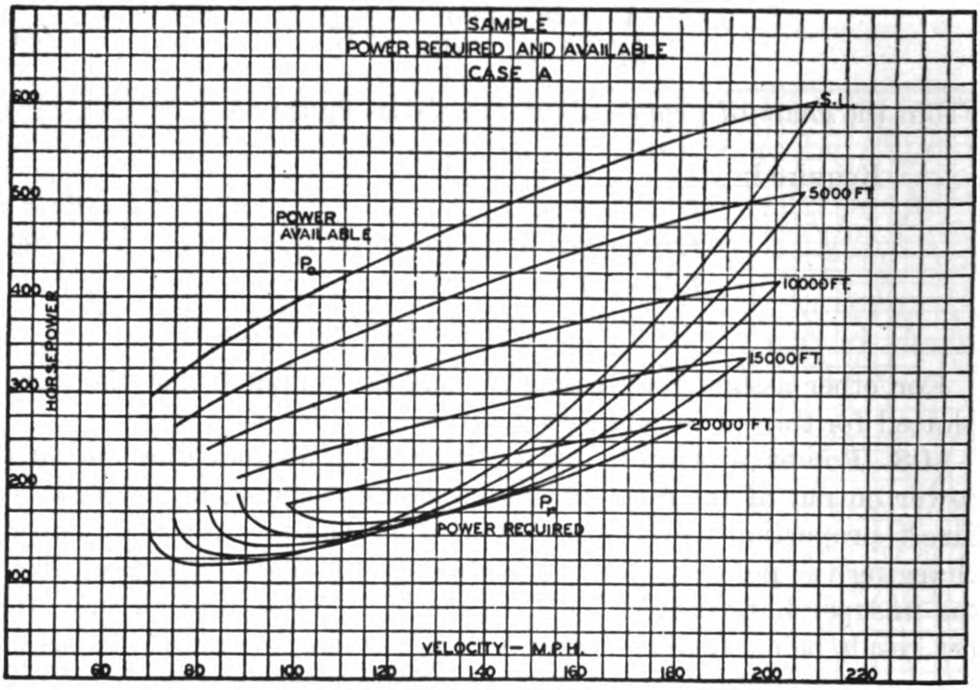


FIGURE 87.—Performance characteristics of monoplane identical with that in figure 86, except engine supercharged to 700 HP at 20,000 feet and propeller selective automatic pitch control.



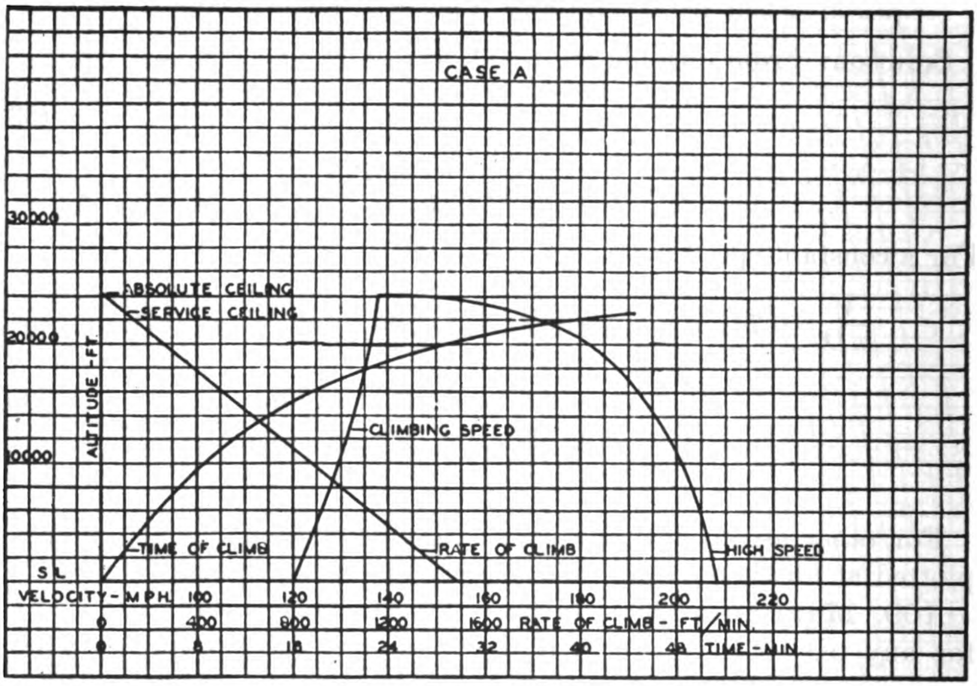
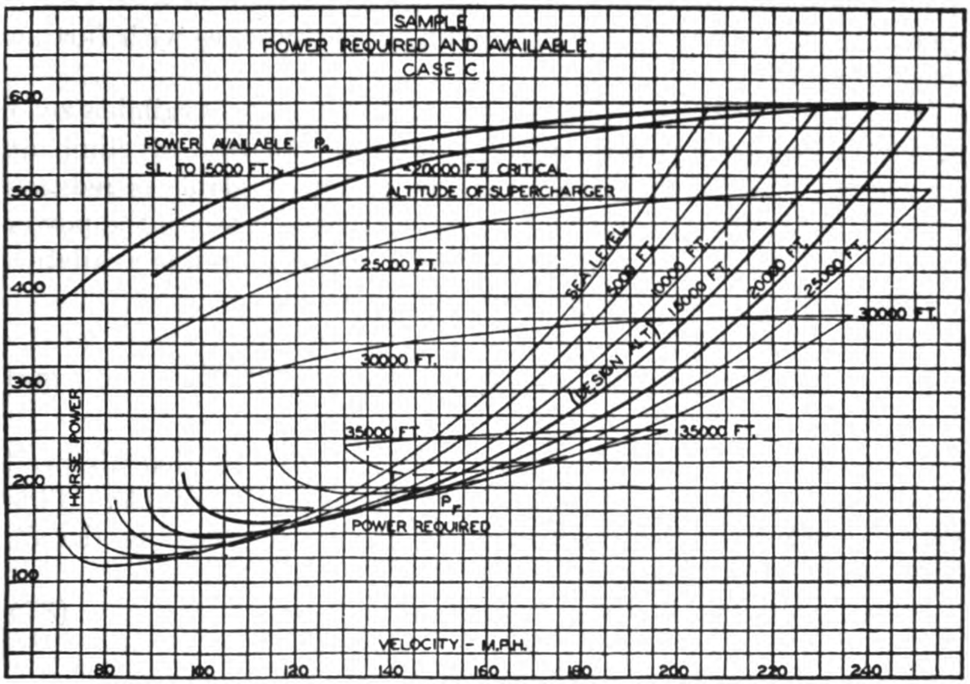


FIGURE 86.—Performance characteristics of a monoplane with 3-blade adjustable, 10-foot propeller; unsupercharged 700 HP engine at 1,650 r. p. m. propeller speed; weight 6,000 pounds; wing area 300 square feet; span 45 feet; A. R. 6.75; airfoil section N. C. A. C. 2218-09.



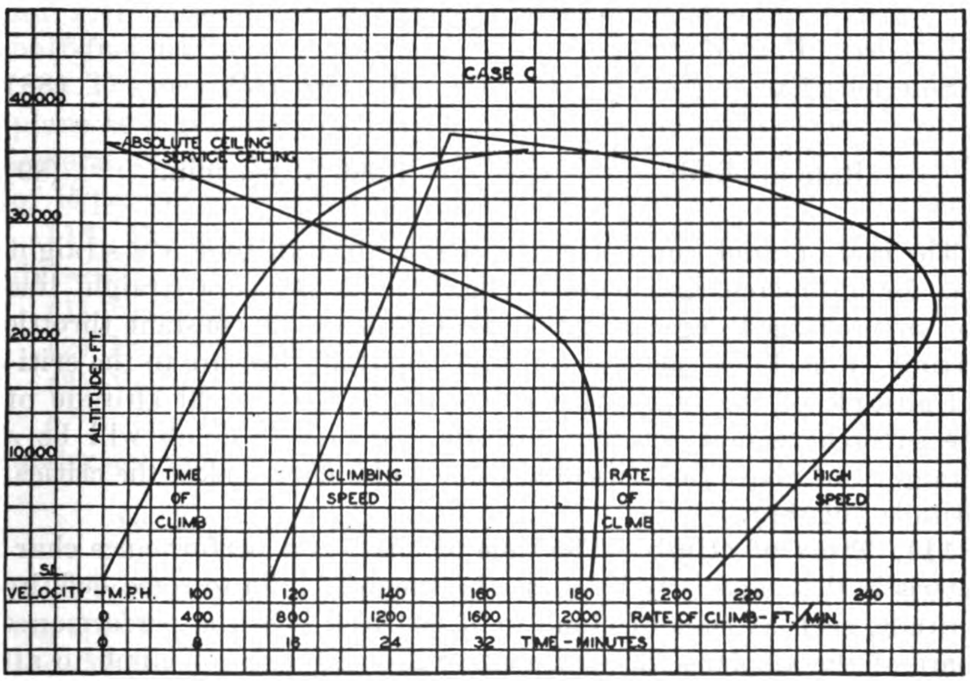


Figure 87.—Performance characteristics of monoplane identical with that in figure 86, except engine supercharged to 700 HP at 20,000 feet and propeller selective automatic pitch control.

level flight increases with altitude up to the critical altitude of the supercharger, after which the maximum speed decreases with further increase in altitude.

110. Rate of climb.—The excess of horsepower available over horsepower required at any speed determines the rate of climb at that speed. If climb is not desired, the power available is reduced by retarding the throttle until a balance is reached between the power available and the power required. Where excess power is available, the rate of climb is determined from the equation,

$$\text{Rate of climb (ft. per min.)} = \frac{HP_{\text{Excess}} \times 33{,}000}{W} \qquad (86)$$

The airspeed of best climb at any given altitude is that airspeed at which the greatest amount of excess power is available. This may be determined from inspection of the graph showing the P_a and P_r curves. (See fig. 83.)

Example: At 140 miles per hour at sea level (87)

$$P_a = 577\ HP.$$
$$P_r = 217\ HP.$$
$$W = 6{,}000\ \text{lb.}$$

Required: Rate of climb.

Solution: Excess $HP = P_a - P_r = 577 - 217 = 360\ HP.$ (88)

$$\text{Rate of climb} = \frac{360 \times 33{,}000}{6{,}000} = 1{,}980 \text{ ft. per min.} \qquad (89)$$

The rate of climb curve when plotted against altitude is a straight line for unsupercharged engines (fig. 86). It is also a straight line for supercharged engines if the climb is made at constant throttle setting. For climbs made at constant manifold pressure to the critical altitude of the supercharger, and above the critical altitude of the supercharger at constant throttle, the rate of climb will be a straight line above the critical altitude and a curve below the critical altitude (fig. 87).

111. Time of climb.—The time of climb is a performance characteristic that is usually listed as the time of climb to some definite altitude, such as time of climb to 15,000 feet. On the performance chart of the airplane the entire curve showing time of climb to all altitudes below the ceiling may be shown.

112. Ceiling.—The absolute ceiling is the limiting altitude which the airplane may attain. At this altitude, no excess power remains

available for climb and the rate of climb becomes zero. The altitude at which the rate of climb is 100 ft./min. is arbitrarily defined as the *service ceiling*.

113. Endurance.—*a*. The endurance of an airplane may be defined as the time it can remain in the air without refueling. It depends on the fuel capacity and the fuel consumption. The installed fuel capacity of a given airplane is fixed by the size of the gas tanks, and the load carrying capacity of the airplane. The fuel consumption will vary according to the operating speed and altitude. In Air Corps specifications it is customary to specify endurance at full throttle at a definite altitude or at a definite operating power output of the engine.

b. Where maximum endurance is required, it is necessary to determine the airspeed for minimum fuel consumption for a given gross weight. It may best be determined by actual flight test. A curve may be plotted of fuel consumption against airspeed and the airspeed for minimum fuel consumption picked by inspection from the curve (fig. 88).

c. As fuel is consumed, the gross weight of the airplane decreases and the airspeed for most economical fuel consumption drops very nearly along a straight line. This curve may be obtained from tests for fuel consumption at reduced loads corresponding to weights at half-fuel load and no-fuel load.

d. The maximum endurance will then be obtained by flying the airplane at a gradually decreased airspeed as the weight decreases. In general, the maximum endurance will be obtained by flying at speeds of 15 percent to 20 percent above the stalling speed.

114. Range.—*a*. The range of an airplane is the distance it can fly without refueling. It depends on—

(1) Fuel capacity.

(2) Fuel consumption.

(3) Velocity and direction of the wind.

b. In Air Corps specifications it is customary to prescribe range under definite conditions of altitude and engine operation.

$$\text{At high speed, range} = \frac{\text{amount of fuel} \times \text{high speed}}{\text{rate of fuel consumption at high speed}}.$$

At operating speed, range = operating speed × endurance at operating speed.

c. Maximum range is a complex function of the airplane, engine, and propeller characteristics. It may be determined by a flight test procedure similar to that in determining endurance. As in the determination of endurance, the fuel consumption test should be repeated at half-

fuel load and no-fuel load. The most economical speed of flight at any condition of fuel load is determined graphically from the fuel consumption curve for any condition of wind. (See fig. 88.)

(1) Lay off the wind to scale on the *X* axis, positive if a head wind, and negative if a tail wind.

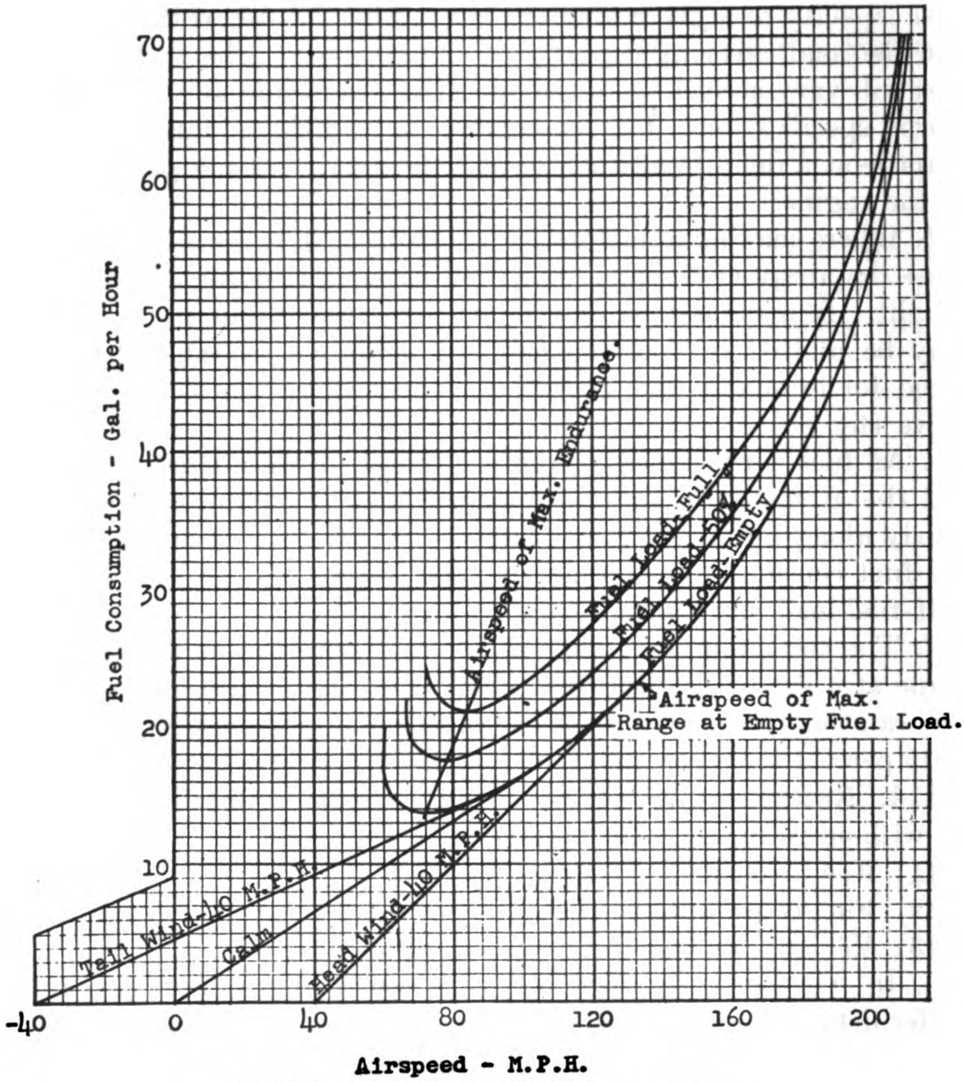


FIGURE 88.—Typical fuel consumption curves.

(2) From the end of the wind vector draw a line tangent to the fuel consumption curve for the immediate weight of the airplane.

(3) The point of tangency is the airspeed for maximum range.

d. The airspeed of flight for maximum range should correspond to the most economical speed for the immediate weight of the airplane. In general, the operating speeds for maximum range occur in the

vicinity of 40 percent above the stalling speed. Head winds increase and tail winds decrease the operating speed for maximum range.

115. Landing characteristics.—*a.* Landing speed is customarily considered to be the stalling speed at sea level, and may be obtained from solution of the formula

$$V_{min}=\sqrt{\frac{391WS}{C_{Lmax}}}\text{(m. p. h.)} \qquad (90)$$

The term W/S is the wing loading and is measured in pounds per square foot. In order to obtain low landing speeds, low wing loading and high maximum lift coefficients are required. These requirements

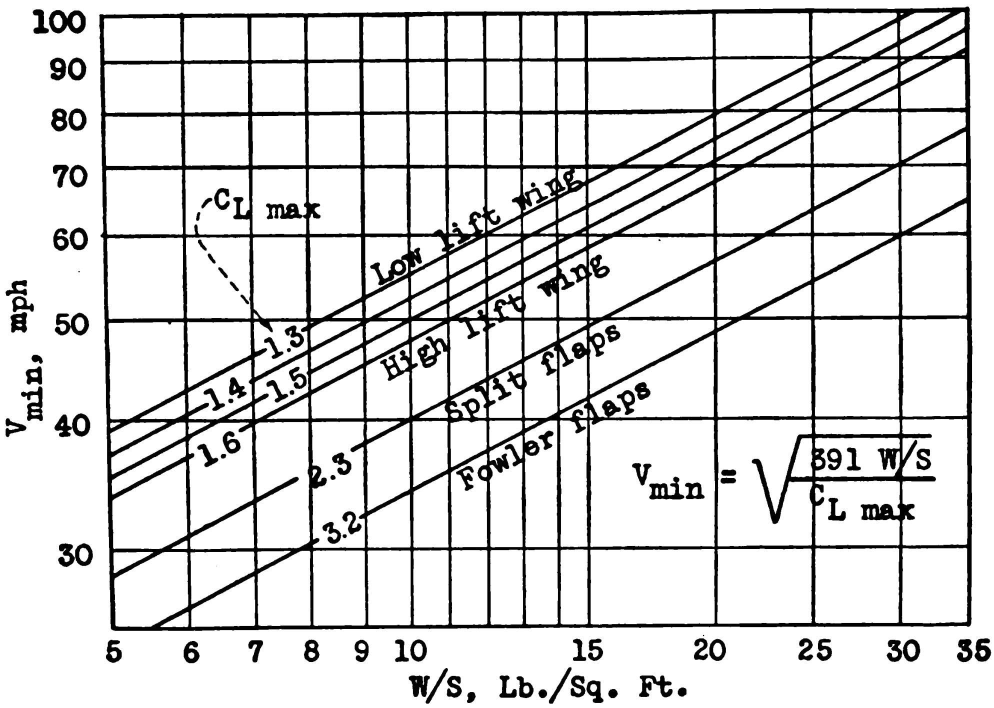


FIGURE 89.—Landing speed and wing loading for various lift coefficients.

lead to large wings and otherwise undesirable wing profiles, so that the tendency is always to design for as high a landing speed as the skill of the pilot and considerations of wear and tear on matériel will permit.

b. The length of roll upon landing is a function of the landing speed and the rate of deceleration. Braking systems have been developed to a high degree of effectiveness and the development of the tricycle landing gear promises to permit the use of large decelerating forces from the braking system immediately upon contact with the ground. The limiting factor on the size of modern airports at the present time

is not the landing speed and length of roll of the modern airplane, but rather the take-off characteristics.

116. Take-off characteristics.—The standard Air Corps performance test for take-off is based on the assumption that take-off speed occurs at 90 percent $C_{L_{max}}$ and that this speed is maintained to clear obstacles at the start of the climb. The distance required to take off is a function of—

a. Wind.

b. Take-off speed (90% $C_{L_{max}}$).

c. Ground friction.

d. Power loading (W/P).

e. Accelerating force (propeller thrust).

Power loading is defined as the gross weight divided by the rated engine horsepower and is measured in pounds per horsepower. The higher the power loading the more sluggish the take-off.

The propeller thrust is the accelerating force at take-off. The fixed pitch propeller is a poor device for securing adequate thrust during the initial stages of the take-off, and the modern heavily loaded aircraft of large size is dependent on the controllable pitch propeller for satisfactory take-off characteristics.

117. Factors affecting performance.—*a.* The chief factors affecting performance may be listed as follows:

(1) The aerodynamic characteristics of the wings, the wing profile, aspect ratio, and wing arrangement.

(2) The wing loading (lbs. per sq. ft.).

(3) The power loading (lbs. per horsepower).

(4) The fineness, or the ratio S/A_e.

(5) The variation of engine power with altitude.

(6) Propeller efficiency.

(7) Fuel consumption.

b. The reduction of wing drag to a minimum is accomplished by selecting a suitable section profile. The choice as between monoplane and biplane has been definitely in favor of the cantilever monoplane for all modern high performance aircraft. The reduction of induced drag through increase in aspect ratio is of greatest importance in heavily loaded airplanes or airplanes designed to operate near their ceiling. It is less important in high speed airplanes of the racer type. The effects of variation in wing loading are—

(1) Low wing loading leads to superiority in climb and ceiling and permits low landing speed.

(2) High wing loading leads to superiority in maximum speed.

c. The effect of high power loading is disadvantageous to the performance characteristics of climb, speed, ceiling, and take-off. High power loading means poor performance.

d. The effects of parasite resistance are most disadvantageous at high speed. It is of greatest importance to keep as much of the parasite resistance as possible out of the slipstream. Airplanes designed for maximum performance in climb or at low cruising speeds can afford to compromise with parasite resistance to achieve other ends, but parasite resistance is a major limiting factor to high speed performance.

e. The variation of engine power with altitude leads to reduced performance at altitude. The use of the supercharger leads to increased weight and consequent slight sacrifice in performance at sea-level, but to greatly increased climb, speed, and ceiling at altitudes above sea level.

f. Increased propeller efficiency leads to more power available for a given power plant and a corresponding all around increase in performance. Since a propeller can only be designed to give its maximum efficiency for a particular condition of flight, it is important that the propeller design be such as to make available the maximum efficiency at the place where it will be needed most. By permitting the engine to operate under more favorable conditions, controllable pitch propellers have greatly increased airplane performance at altitude and in climb at sea level.

g. Decrease in specific fuel consumption increases both endurance and range. Fuel economy is of paramount importance in airplanes designed for maximum possible range and endurance, and relatively less important in aircraft designed for short range operation only.

Section VII

EQUILIBRIUM, STABILITY, AND CONTROL

118. Reference axes.—The motion of the airplane may be studied with reference to three axes fixed in the airplane with their origin at the center of gravity:

a. The longitudinal or X axis is drawn through the center of gravity parallel to the relative wind.

b. The lateral of Y axis is perpendicular to the X axis and is horizontal when the airplane is on an even keel.

c. The vertical or Z axis is drawn through the center of gravity perpendicular to both the X axis and the Y axis.

119. Angular motion.—In flight the airplane may not only move from one point in space to another (motion of translation), but it may also rotate about its center of gravity. In studying the motion of the airplane, of interest are not only translational velocities and accelerations but also rotational velocities and accelerations. (See fig. 1.)

a. Roll—Angular movement about the X axis is called "roll" and is considered positive when the airplane banks to the right.

b. Pitch.—Angular movement about the Y axis is called "pitch", positive if the nose of the airplane rises, negative if it falls. A positive pitching moment or a stalling moment is a moment which tends to make the nose of the airplane rise. A negative pitching moment or a diving moment is a moment which tends to make the nose of the airplane fall.

c. Yaw.—Angular movement about the Z axis is called "yaw", considered positive when the turn is to the right.

120. Angle of incidence.—The angle of incidence is the angle between the chord of the wing and an arbitrary reference line fixed in the airplane. This reference line is usually drawn through the center of gravity parallel to the crankshaft of the engine and called the longitudinal axis of the airplane. This axis usually coincides

with the X axis as defined in paragraph 118 when the airplane is in level flight at normal cruising speed. The angle of incidence is built into the airplane structure and must not be confused with angle of attack. The angle of incidence is usually so designed that at normal cruising speed in level flight the longitudinal axis of the airplane is horizontal.

121. Relative wind.—In calm, still air, the direction of the relative wind is opposite to the flight path of the airplane referred to the ground. When the wind blows, the path of the airplane referred to the ground is not the same as the path referred to the moving air. The aerodynamic forces on the airplane are always a function of the relative wind and not of the ground wind.

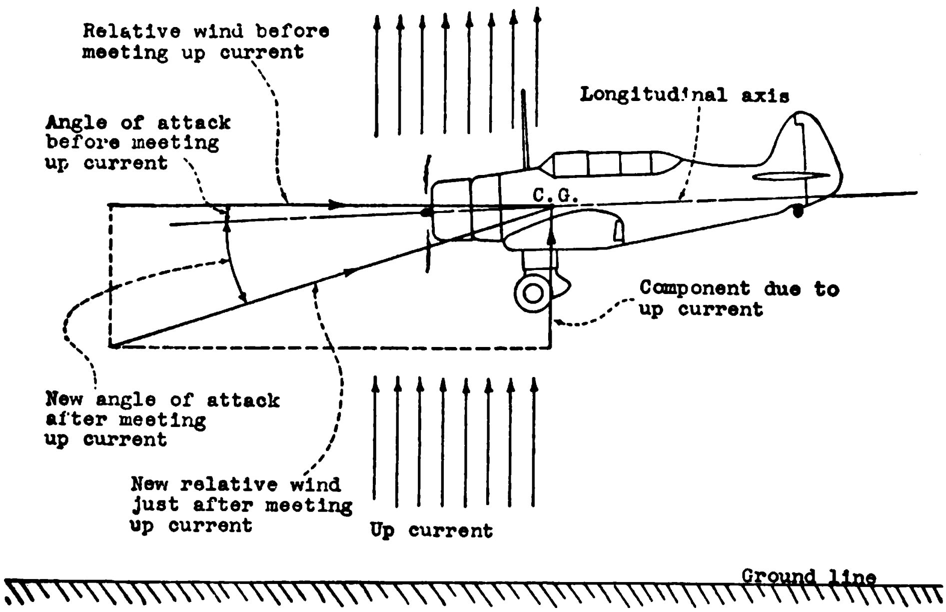


FIGURE 90.—Effect of gusts on relative wind.

122. Forces acting on complete airplane in level flight.—In unaccelerated flight, three fundamental equations of mechanics must be satisfied.

$$\Sigma H=0 \qquad \Sigma V=0 \qquad \Sigma M=0$$

The horizontal forces in level flight are the propeller thrust acting in a forward direction and the sum of all the drag forces acting to the rear. For equilibrium,

$$\text{Thrust}=\text{total drag}$$

The vertical forces in level flight are the force of gravity (equal to the weight of the airplane), the lift of the wings, and the tail load (usually a down load). For equilibrium,

$$\text{Lift}=\text{weight}+\text{tail load.}$$

The center of gravity is taken as the origin of moments. The third requirement for equilibrium (fig. 97) is such that the sum of all moments must equal to zero.

$$(\text{Thrust}\times c)+(\text{drag}\times b)+(\text{tail load}\times e)=(\text{lift}\times a).$$

Of the forces acting on the airplane, the lift and weight remain nearly constant, the thrust can be changed by manipulation of the engine throttle, the drag forces are a function of the speed of flight. The center of gravity can be shifted only by a redistribution of weights.

The manipulation of the elevators by the pilot places at his disposal a powerful means of changing the tail load, and since the moment arm of the tail load is comparatively long, large changes in tail load moment can be made at will by the pilot. The equilibrium of the airplane is maintained by the adjustment of the tail load

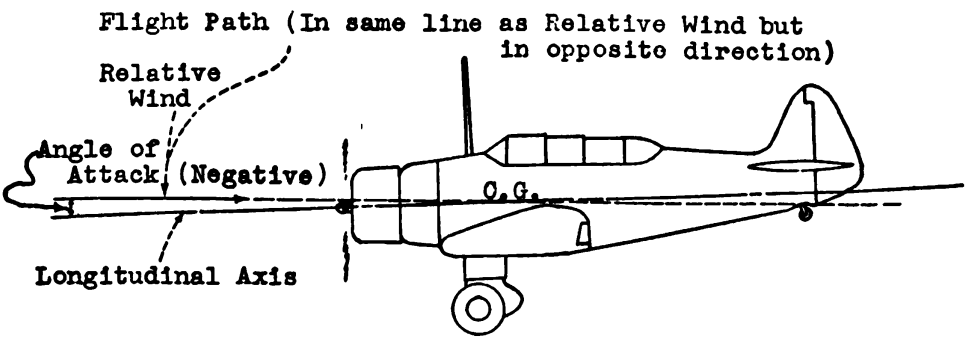


FIGURE 91.—Level flights at high speed in still air.

moment to neutralize the moments of the remaining forces in such manner that the condition $\Sigma M=0$ is satisfied.

123. Equilibrium in climb.—In a climb, the center of pressure at the larger angles of attack moves forward thus decreasing the moment arm of the lift force. A corresponding decrease in tail load moment is required for equilibrium. The fundamental forces may be resolved into components parallel to and perpendicular to the relative wind, and the three equations of equilibrium become

$$\text{Thrust}_H=\text{drag}+\text{weight}_H$$

$$\text{Lift}+\text{thrust}_V=\text{weight}_V+\text{tail load}$$

$$(\text{Thrust}_H\times c)+(\text{thrust}_V\times f)+(\text{drag}\times b)+(\text{tail load}\times e)=\text{lift}\times a$$

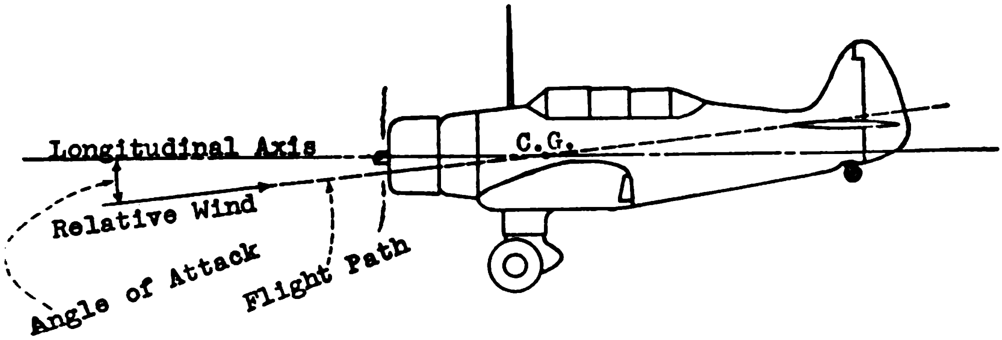


FIGURE 92.—Climbing in still air.

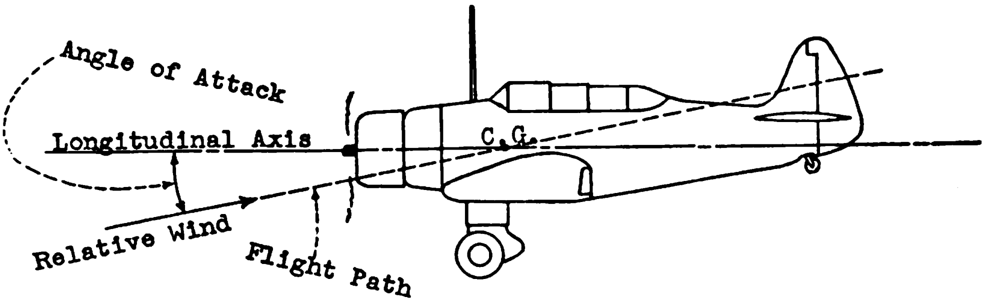


FIGURE 93.—Gliding in still air.

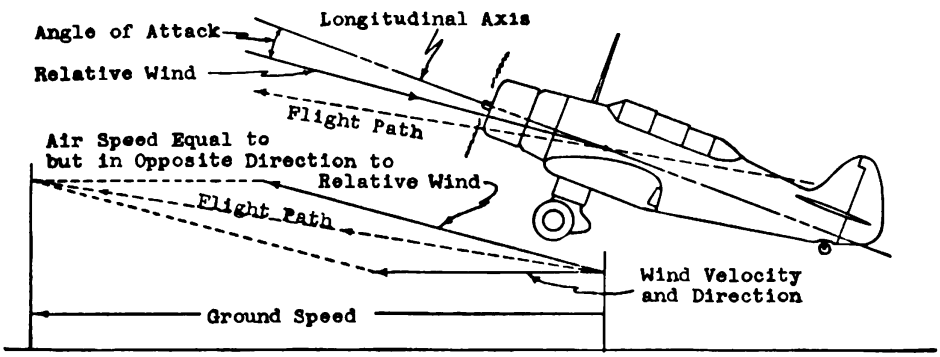


FIGURE 94.—Climbing with a wind.

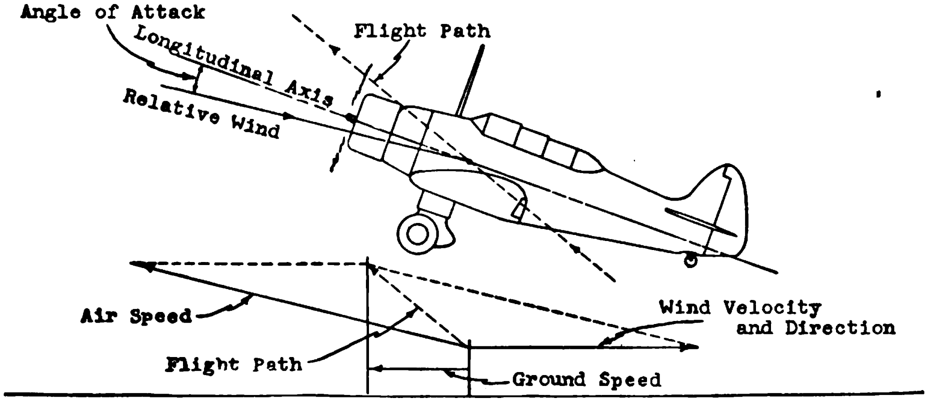


FIGURE 95.—Climbing into a wind.

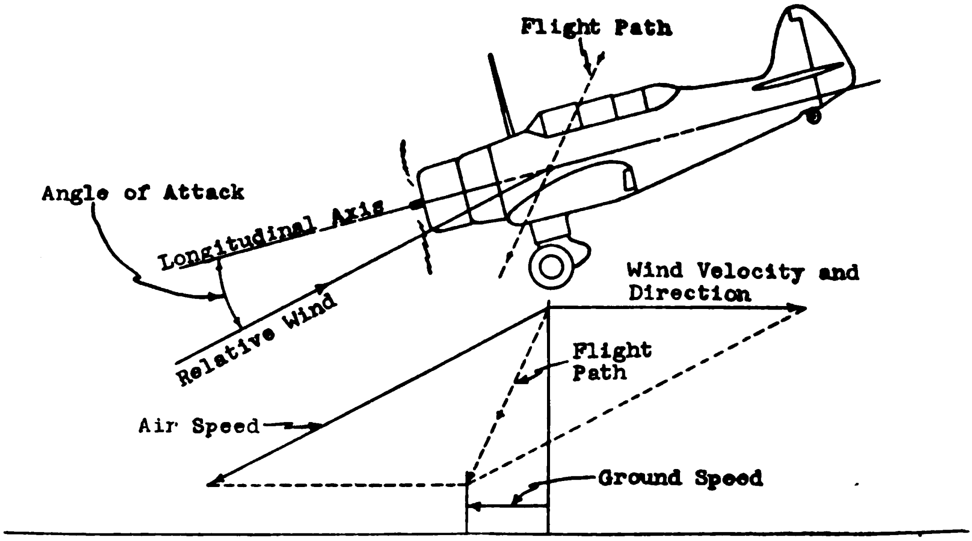


FIGURE 96.—Gliding into a wind.

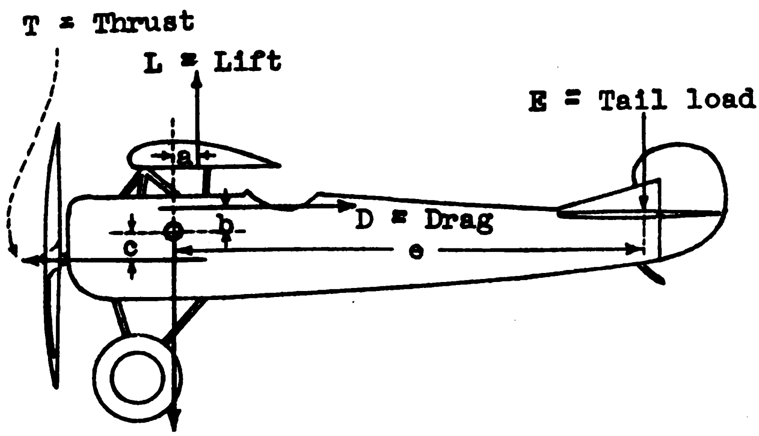


FIGURE 97.—Resultant forces on airplane in level flight.

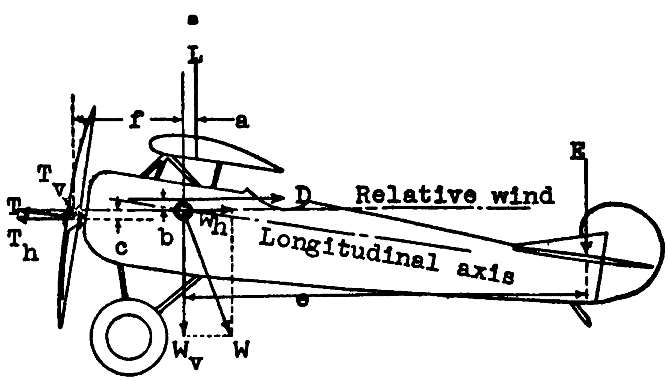


FIGURE 98.—Resultant forces on airplane in climb.

where the subscripts H and V indicate the components of the forces parallel to and perpendicular to the relative wind respectively.

124. Equilibrium in glide.—In a glide without power, the component of the weight parallel to the relative wind becomes the motive power, and the equations of equilibrium may be written

$$\text{Weight}_H=\text{drag}$$

$$\text{Lift}=\text{weight}_V+\text{tail load}$$

$$(\text{Drag}\times b)+(\text{tail load}\times e)=(\text{lift}\times a).$$

It will be observed that the cotangent of Θ, the angle of inclination of the flight path to the horizontal is,

$$\text{Cot }\theta=\frac{\text{Weight}_V}{\text{Weight}_H}=\frac{\text{Lift}-\text{tail load}}{\text{drag}}=\frac{L}{D}\text{ ratio of the complete airplane.}$$

If the best gliding angle be defined as the flattest gliding angle, the angle of best glide occurs at the speed where the L/D ratio for the complete airplane is a maximum. Since the L/D ratio is not affected by the air density, the angle of best glide is the same for all altitudes. The further conclusion may be drawn that, since the L/D ratio is purely an aerodynamic characteristic of the external shape of the airplane, the angle of best glide is the same regardless of the total weight of the airplane, that is, whether with full load on board or empty. The speed of best glide is affected by air density and loading conditions, but not the gliding angle.

125. Equilibrium in dive.—In a vertical dive there is no resultant lift force, but a large down load on the front spar of the wing and an up load on the rear spar require a down load on the tail surfaces for balance. The equations of equilibrium may be written

$$\text{Weight}=\text{drag}$$
$$\text{Lift}_R=\text{lift}_F+\text{tail load}$$
$$(\text{Lift}_F\times a_F)+(\text{Lift}_R\times a_R)=(\text{drag}\times b)+(\text{tail load}\times e)$$

In a vertical dive, the velocity will accelerate until the drag equals the weight. The velocity at which a state of equilibrium is reached is the *terminal velocity*. Due to the decrease of air density with altitude, the terminal velocity for a given airplane will be greater at high altitudes than at sea level.

126. Effect of throttle setting on balance.—In general, a change in throttle setting disturbs the balance of the airplane and

requires a readjustment of the stabilizer or elevator setting. The factors contributing to the change in balance are many.

a. Unless the line of action of the thrust force passes through the center of gravity, the thrust moment will change with throttle setting.

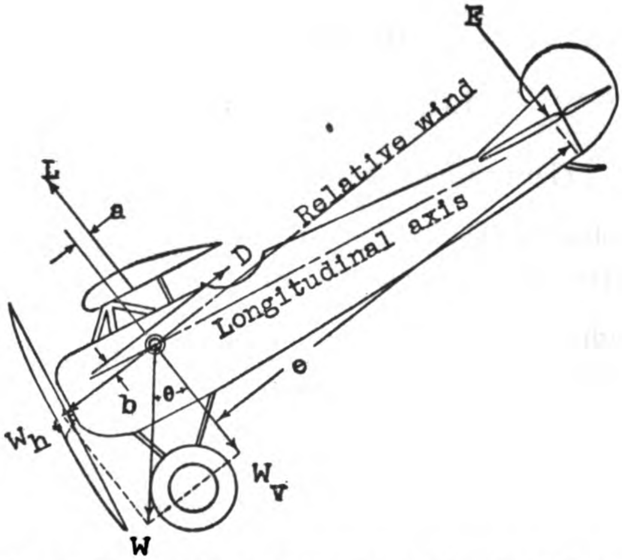


FIGURE 99.—Resultant forces on an airplane in a glide.

b. The slipstream velocity changes with throttle setting. Since the tail surfaces are usually located in the slipstream, any change in slipstream velocity directly affects the load on the horizontal tail surfaces and a corresponding change in the tail load moment occurs.

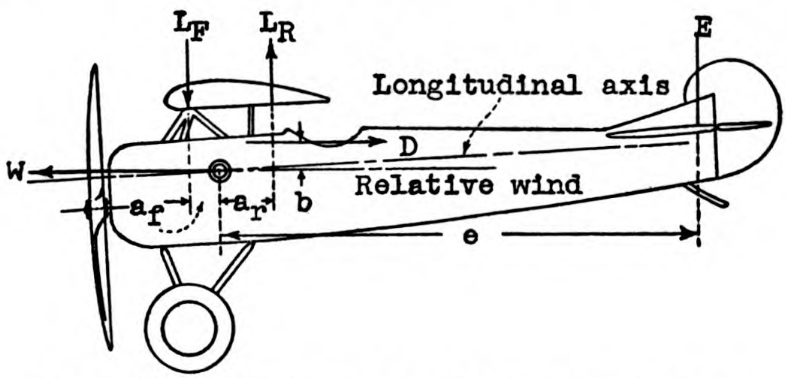


FIGURE 100.—Resultant forces on an airplane in a vertical dive.

c. The change in speed of the airplane with change in the engine power available results in a shift of the center of pressure of the air forces on the wings with consequent changes in the moments of these forces.

d. The angle of downwash ϵ is the angular deflection of the airstream due to the lift produced by the wings. At slow speeds the angle ϵ is larger than at high speed. Any change in speed, the result of a change in throttle setting, will then produce a change in the angle of downwash ϵ. As the tail surfaces of the conventional airplane are located in the downwash, any change in ϵ contributes to a change in tail load moment.

e. Unless the line of action of the parasite drag passes through the center of gravity, the change in drag produced by change in speed will result in change of the parasite drag moment.

f. In some airplanes the disturbing factors may tend to neutralize each other, so that the effect of change of throttle setting on balance will be small. If the disturbing factors cumulate, the balance of the airplane will be greatly influenced by throttle setting, requiring large changes in the setting of the horizontal stabilizer or use of the elevator controls to bring the airplane in to equilibrium. It is a

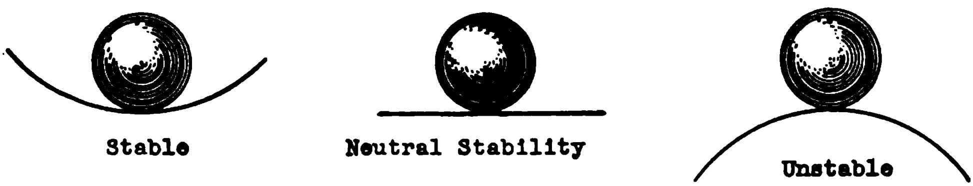


FIGURE 101.—Types of static stability.

problem of design to adjust these factors so that the flight characteristics of the airplane will be satisfactory.

127. Definition of stability.—A body is said to be in stable equilibrium if, when slightly disturbed from a condition of equilibrium, forces or moments are developed of a character such that they tend to restore the body to its original state. In a condition of neutral stability, after disturbance, the body tends neither to return to its original state nor to move further from it. A state of equilibrium is said to be unstable when after disturbance, the forces and moments tend to move the body further away from its original state.

Thus a round ball at the bottom of a convex surface is in stable equilibrium, for if it is disturbed it will roll back to its original position. If the ball is on a flat level surface it is in neutral equilibrium, for if displaced from its original position it neither returns to its original position nor will the disturbance tend to increase. If the ball is balanced at the top of a concave surface it is in unstable equilibrium, for if disturbed the forces acting on the ball tend immediately to increase the disturbance.

128. Static and dynamic stability.—The conditions discussed in paragraph 127 are the conditions of *static stability*. *Dynamic stability* treats with the oscillations that are set up as the result of a system of restoring forces or moments when a body is disturbed.

A pendulum, when disturbed from its position of rest, is acted upon by the forces of gravity tending to restore it to its original position of rest. The system is statically stable. But the pendulum does not return to its original position and stop, it oscillates. Ordinarily the forces of friction damp out the oscillations, the amplitude of each oscillation is less than the one before, the system is not only statically stable but dynamically stable. In the extreme case where the forces of friction are so large that the pendulum returns slowly to its position of rest without oscillation, its dynamic stability is *dead beat*.

If, at each swing of the pendulum, a small force is applied as the bob starts on the downward swing, the damping forces of friction may be counterbalanced and the pendulum will swing indefinitely. Such a system is statically stable, but has neutral dynamic stability.

It is quite possible that the force applied to the bob at each end of the swing may be larger than that necessary merely to counterbalance the forces of friction, in which case the amplitude of the oscillations will increase. Although this system is statically stable, it is dynamically unstable.

129. Motion of airplane.—The motion of the airplane may be classed as statically stable or unstable, and if statically stable may in addition be classed as dynamically stable or unstable. This classification may be made for the motion of the airplane about each of the three principal axes, the longitudinal or pitching motion, the lateral or rolling motion, and the directional or yawing motion.

130. Requirements for longitudinal stability.—In normal level flight, the airplane is balanced longitudinally by adjustment of the horizontal tail surfaces. If the attitude of the airplane then be slightly disturbed by a gust or by temporary manipulation of the elevator control, the longitudinal motion, if not checked by further manipulation of the elevator control, may proceed in one of five ways:

a. The airplane may return to its original attitude without oscillation. (Statically stable and dead beat dynamically stable.)

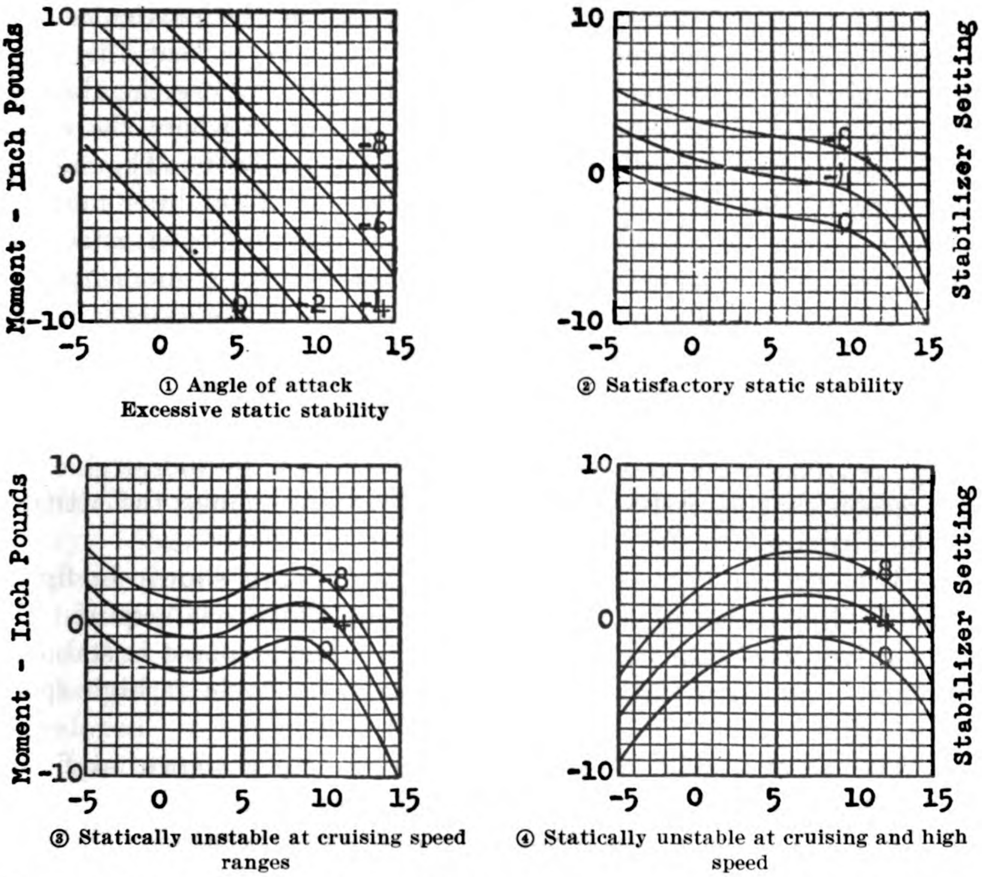
b. The airplane may show no tendency to change its new attitude. (Neutral static stability.)

c. The airplane may oscillate with decreasing amplitude until it assumes its original flight attitude. (Statically and dynamically stable.)

d. The arplane may oscillate with increasing amplitude. (Static stability, dynamic instability.)

e. The angle of attack may continue to increase or continue to decrease depending on the sense of the original disturbance. (Static instability.)

The airplane in its longitudinal motion may be statically and dynamically stable but be unstable in roll or yaw. However, in its pitching motion, the cases of dynamic instability are extremely rare.



① Angle of attack
Excessive static stability

② Satisfactory static stability

③ Statically unstable at cruising speed ranges

④ Statically unstable at cruising and high speed

FIGURE 102.—Typical pitching moment curves about center of gravity from wind tunnel tests of model airplanes.

The oscillations damp out with greater or less rapidity according to the airplane design. But there are frequent cases in service aircraft of static instability in pitch, practically without exception the result of faulty or ill-considered design. Such airplanes require constant effort on the part of the pilot to maintain steady flight.

131. Pitching moment curves.—It is common practice to run a wind tunnel test on the model of the complete airplane to obtain pitching moment curves. This test represents quite accurately the

condition of flight with power off, and by estimating the effects of the thrust moment and slipstream the designer is enabled to determine the longitudinal stability characteristics of a proposed airplane while it is still in the drafting board stage. The wind tunnel test of the model is run for several different settings of the horizontal stabilizer. The pitching moments about the center of gravity of the full scale airplane are then plotted as ordinates against angle of attack as abscissae. The angle of attack at which the curve cuts the X axis is the point where the equation $\Sigma M=0$ is satisfied and is the angle of attack for equilibrium in flight for the particular stabilizer setting. The criterion for static stability is that the slope of the moment curve be negative. At all points where the slope is positive, static instability is indicated. At points where the curve is parallel to the X axis, neutral stability is indicated. The steeper the slope of the curve, the greater the change of pitching moment when the attitude of the airplane, that is, the angle of attack, is disturbed, and consequently the larger the restoring moments. A brief visual inspection of the curve of pitching moments is sufficient to disclose a great deal of information about the stability and flying characteristics of an airplane.

a. The general type of pitching moment curve shown in figure 102① is illustrative of excessive stability which is undesirable for the reason that excessive forces are required to change the attitude of the airplane.

b. The general type of pitching moment curve shown in figure 102④ is illustrative of a type of instability which has acquired the descriptive title "catastrophic instability". The airplane is stable at the higher angles of attack but is extremely unstable at high speed or in a dive.

c. The general type of pitching moment curve shown in figure 102③ is illustrative of a type of instability that is characteristic of some airplanes in the cruising speed range. Steady flight at cruising speeds is difficult to maintain in an airplane of this type. The airplane has a tendency to "hunt" and requires constant effort on the part of the pilot for control.

d. The type of pitching moment curve shown in figure 102② is in general the most desirable. The pitching motion is stable so that the airplane tends to maintain a constant flight attitude, but the forces required for longitudinal control throughout the flight range are small and within the physical capabilities of the pilot.

132. Factors influencing longitudinal stability.—*a.* The chief factors influencing longitudinal stability are as follows:

(1) The larger the ratio of horizontal tail area to wing area the greater the stability.

(2) The less the center of pressure of the wings shifts with angle of attack, the greater the stability of the complete airplane.

(3) The greater the distance from the tail surfaces to the center of gravity the greater the degree of stability.

(4) The greater the aspect ratio of the horizontal tail surfaces the greater the degree of stability.

(5) Downwash has a very marked adverse effect on stability.

(6) The type of airfoil section used for the horizontal tail surfaces influences stability.

(7) The vertical location of the center of gravity with respect to the wing chord has marked influence on stability. The tendency of a center of gravity location above the wing chord is for the system to be less stable than where the center of gravity is below the wing chord. The prevalent conception that this tendency is due to a pendulum effect is, however, entirely erroneous.

(8) The horizontal location of the center of gravity with respect to the wing chord has a marked influence on stability. The general tendency in modern design is to fix the location of the center of gravity in the range 25 to 30 percent from the leading edge of the mean aerodynamic chord. Movement of the center of gravity toward the trailing edge leads to instability.

(9) The slipstream and the thrust moment have their effects on stability. The stability characteristics of airplanes vary to a considerable degree with power on and power off.

b. In service aircraft, a distribution of the load carried in a manner other than the designed distribution may so shift the center of gravity of the complete airplane that very undesirable flight characteristics are developed. A slight shift in center of gravity location to the rear may change the pitching moment characteristics from the type shown in figure 102② to those shown in figure 102③. For this reason, many aircraft of the cargo carrying type have loading distribution schedules posted for the information of the pilot who is required to supervise the loading of the aircraft in such manner that its flying characteristics may not be dangerously impaired.

133. Lateral stability and directional stability.—The motions of yaw, roll, and sideslip are all so interrelated that lateral stability and directional stability can only with great difficulty be considered independently. The same forces that produce motion in roll also produce motion in yaw, although these forces are frequently more effective in their results on the one motion or the other. Static lateral stability

may be defined as the characteristic of the airplane which tends to restore the airplane to an even keel after it has been tipped sideways. The airplane may return to an even keel and then tip to the other side, the motion being oscillatory in the same sense as oscillations in pitch. Should the oscillations damp out, the lateral motion is dynamically stable. In the lateral motion, the restoring moments are due to the

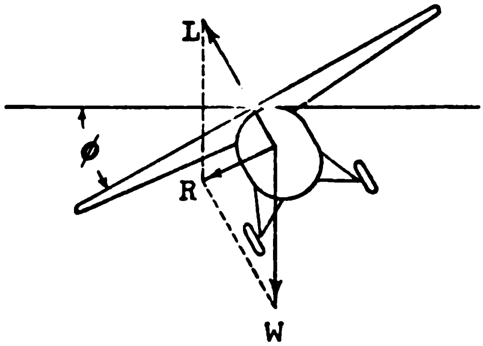


FIGURE 103.—Forces on an airplane at an angle of roll.

resulting sideslip which occurs when the airplane is tilted. The sidewise component of the relative wind when sideslip occurs may be utilized to secure lateral stability as follows:

a. By raising the wing tips so that a dihedral angle is formed by the wing, the lower wing acquires additional lift thus producing a restoring moment. This is illustrated in figure 104.

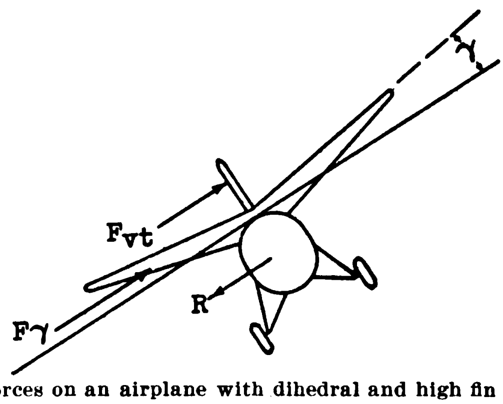


FIGURE 104.—Forces on an airplane with dihedral and high fin area in a sideslip.

b. Distribution of a larger vertical fin area above the center of gravity than below it places the center of resistance of the fin area in a sideslip above the center of gravity and a restoring moment is thus produced when sideslip occurs.

c. The concentration of a large fin area in the vertical tail surfaces far to the rear of the center of gravity produces a yawing moment in sideslip and the airplane acts much like a weather vane. As the yaw-

ing effect produced by the vertical tail surface heads the airplane into the wind, one wing moves forward faster than the other and thus a lifting force is produced tending to increase the bank. The increased bank produces increased sideslip, the cycle repeating itself and resulting in a motion known as spiral instability.

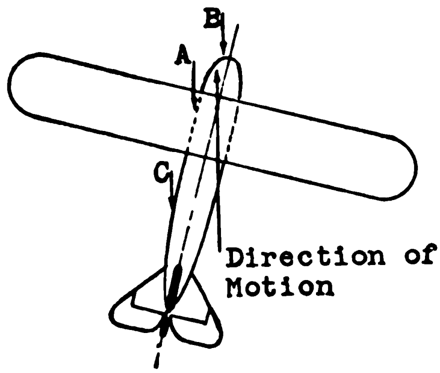


FIGURE 105.—Forces on vertical fin surfaces at angles of yaw.

d. Directional stability is secured by so distributing the vertical fin area that the resultant air forces in sideslip act to the rear of the center of gravity and so force the nose of the airplane into the wind. As indicated in *c* above, excessive directional stability combines with the rolling motion to produce spiral instability. The proper adjustment of vertical fin area to secure directional stability and to avoid

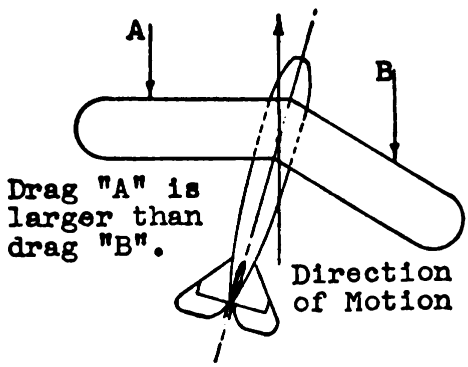


FIGURE 106.—Force on wings with sweepback at angles of yaw.

spiral instability is a problem that the designer must successfully solve if the flight characteristics of the airplane are to be satisfactory.

e. Sweepback in modern aircraft is a device which the designer uses principally to secure the proper horizontal location of the center of gravity with respect to the mean aerodynamic chord. It incidentally has an effect on directional stability since in a sideslip the drag forces on the two wings are unequal and a stable restoring moment

in yaw is produced. Conversely, a negative sweepback has an unfavorable effect on directional stability.

134. Dynamic instability in yaw and roll.—A form of dynamic instability in roll and yaw is occasionally observed which is the result of the vertical tail surfaces being blanketed by the fuselage, usually of the large cargo type. Due to the deflection of the airstream by the fuselage past the vertical tail surfaces, the airplane is unstable in yaw for a limited range of angles. As the airplane yaws, the vertical tail surfaces move out past the dead air space directly behind the fuselage and a stable restoring moment is produced. The resultant motion is a constant hunting in direction and a constant rolling motion from side to side due to the unbalanced lift forces on the wings as the airplane oscillates.

135. Flutter and buffeting.—*a.* Wings with large unbraced overhang and cantilever monoplane wings are subject to large deflections at the wing tip. As the center of pressure shifts along the chord, the spars deflect by unequal amounts with resultant changes in angle of attack of the portion of the wing toward the tip. This tends to reduce the effectiveness of the aileron control since the change in center of pressure location produced by operation of the ailerons produces a torsional deflection of the wing tip and a change in angle of attack.

b. The torsional deflection of the wing tip induced by aileron operation in some cases results in a dynamically unstable oscillation known as "wing flutter". As the wing deflects, the inertia of the aileron causes its trailing edge to lag behind the motion of the wing, producing a change in effective camber of the wing and a shift of the center of pressure with further wing deflection. The elastic properties of the wing cause it to vibrate, and when the inertia characteristics of the aileron control system cause it to vibrate at the same period as the wing structure, an unstable oscillation of large amplitude is rapidly built up which will disintegrate the wing structure unless checked. The methods used to eliminate this form of instability are as follows:

(1) Design the wing structure for a large degree of torsional stiffness.

(2) Balance the aileron statically about the hinge line by placing balancing weights in the portion of the aileron ahead of the hinge.

(3) Place the aileron control system under considerable initial tension to remove all lost motion.

c. In flight, torsional oscillation or "wing flutter" usually occurs at the higher speed ranges or in a dive. The remedy available to the pilot is promptly to reduce speed and fly at the larger angles of attack until a landing can be effected.

d. A similar oscillation or flutter occurs in propeller blades. In this case the exciting force is supplied by the engine, usually the impulse of the explosion in each cylinder. When the period of the exciting force coincides with the elastic period of vibration of the propeller, large deflections are produced which eventually result in propeller failure. The remedy is to design the engine so that the magnitude of the exciting forces is small and of such frequency that resonance with the natural periods of vibration of the propeller will not occur within the operating speed range.

e. Excessive engine vibration has been known to furnish the exciting force resulting in flutter of wings in much the same manner as aileron flutter. The remedy is to reduce engine speed to avoid the resonant period and the flutter will die out.

f. The unstable airflow behind the wing at stalling angles of attack has in some airplanes furnished a variable exciting force resulting in a vibration of the tail surfaces known as "buffeting". Surfaces located in the propeller slipstream may also be excited to excessive vibration by the periodically varying changes in slipstream velocity due to each individual propeller blade.

g. The number and variety of the phenomena that can be classed as cases of dynamic instability are large and require attention and correction in every new type of aircraft.

136. Control.—Control of the motion of the airplane is secured through manipulation of any one or all three sets of control surfaces, that is, the elevator, the rudder, and the ailerons. Control should be positive and effective throughout the flight range. Control and stability are interdependent. Where stability is excessive, powerful controls are necessary to effect changes in attitude. It was formerly considered necessary deliberately to design longitudinally unstable airplanes for types where extreme maneuverability was an essential requirement. A better understanding of the problem, however, has shown that there is no necessity for the sacrifice of a moderate degree of stability to secure service aircraft that will perform with the required degree of maneuverability.

137. Design of control surfaces.—*a.* A prime factor in securing easy and effective control is to design the control system so that large air loads are the result of a small amount of physical exertion by the pilot. By hinging a relatively small movable flap along the rear edge of a larger fixed surface, a change in the setting of the flap has the effect of changing the effective camber of the entire surface. The major part of the air load is carried by the fixed surface and relatively small loads are transmitted to the control system by the mov-

able flap. This method of designing control surfaces has become standard for nearly all aircraft.

b. The hinge moments required to move the control flaps may be further reduced by placing a portion of the surface of the movable

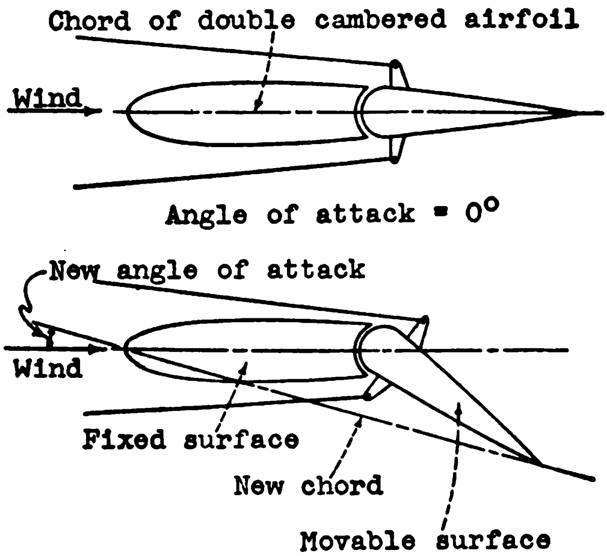


FIGURE 107.—Effect of movable flap of a control surface in changing effective camber.

control flap ahead of the hinge line. The air loads ahead of the hinge line and behind the hinge line tend to balance each other.

c. The use of trimming tabs to balance the airplane is coming into increased use as a substitute for adjustable stabilizing surfaces. The

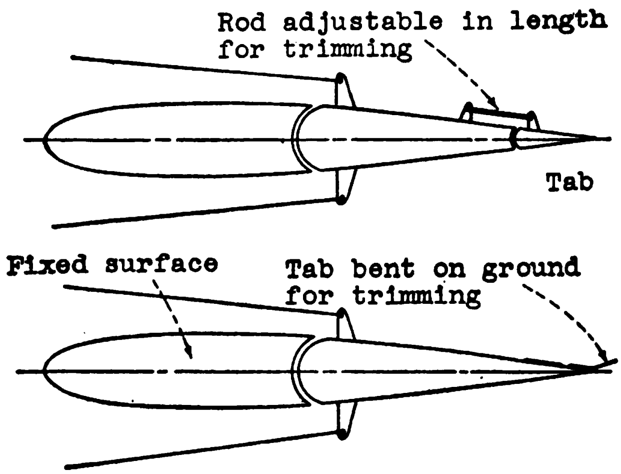


FIGURE 108.—Fixed trim tab.

tab is a small adjustable surface fixed at the trailing edge of the movable control surface. The air load on the tab produces a moment about the control hinge and deflects the control surface producing a

control moment but without the exertion of effort on the part of the pilot. The tabs may be adjustable on the ground only, as is usually the case with aileron tabs, or may be adjustable at the will of the pilot in flight, as is frequently the case with rudder and elevator control tabs.

d. The flettner control is a trimming tab adjustable by the pilot in flight. By this means the rudder control may be adjusted to relieve the pilot of the constant strain of correcting for an unbalanced yawing moment, or the elevator tab may be used to trim the longitudinal balance of the airplane for different loading conditions or speeds of flight.

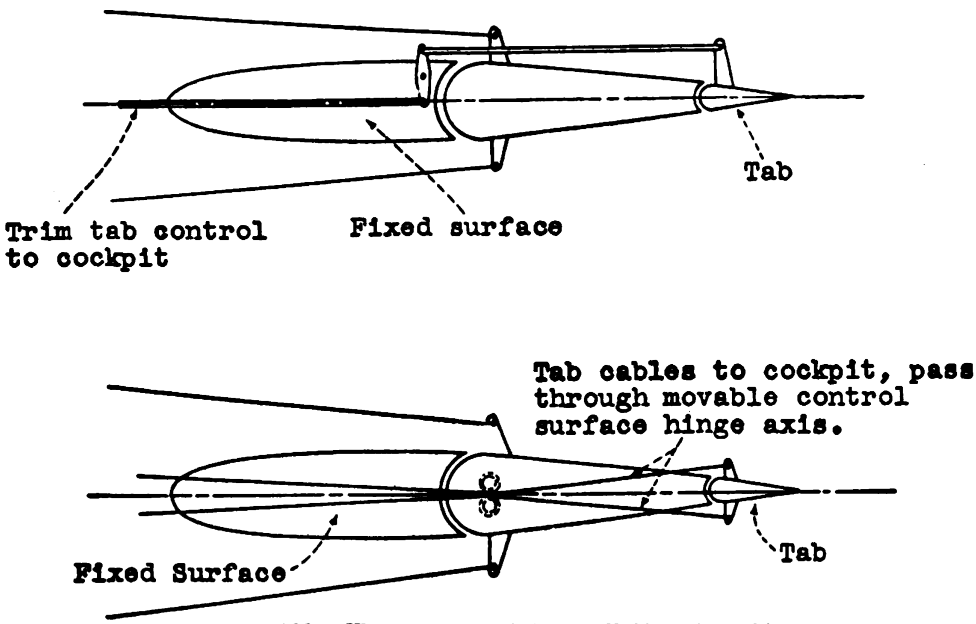
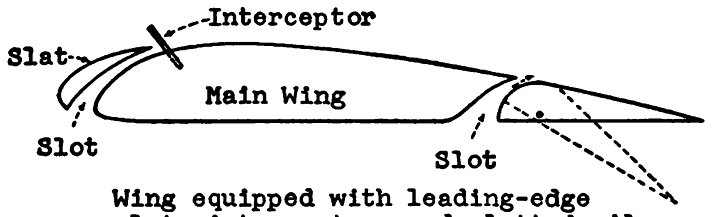


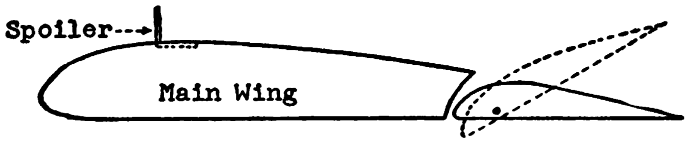
FIGURE 109.—Flettner control (controllable trim tab).

e. The aileron trimming tab eliminates the necessity for the wash-in or wash-out of angle of incidence to counteract the effects of engine torque, and is a much simpler method of securing lateral balance.

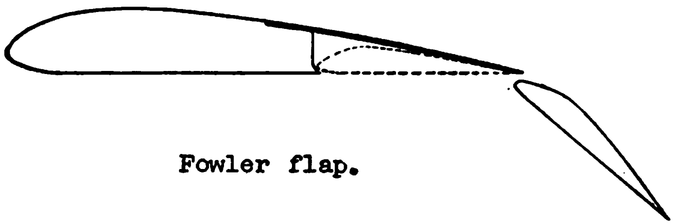
138. Longitudinal control.—The horizontal tail surfaces must be designed to give adequate longitudinal stability as well as to meet the requirements of control. The tail surfaces are also most effective in damping the pitching oscillations. The distribution of area between the fixed stabilizer and the movable elevator is adjusted so that the smallest elevator feasible with adequate control is used. This arrangement results in minimum control forces. The stabilizer-elevator combination must produce pitching moments sufficient to



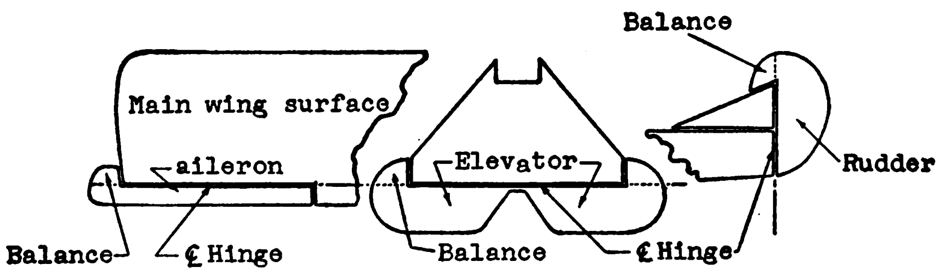
Wing equipped with leading-edge slot, interceptor, and slotted aileron.



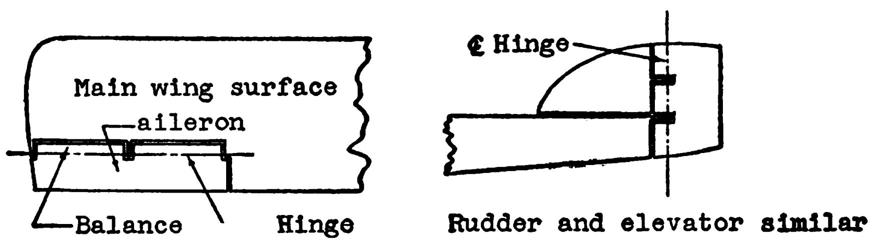
Wing equipped with spoiler and Frise aileron.



Fowler flap.



The "overhang" type of control surface balance.



The Handley-Page type of balance.

Figure 110.—Types of control surfaces.

pull the airplane out of a steep dive and to get the tail down in landing.

139. Directional control.—Directional control is effected by the rudder-fin combination, the same considerations in general governing the distribution of the total area as in the case of the stabilizer-elevator combination. The slipstream as it leaves the propeller tends to follow a helical path, and consequently exerts a greater pressure on one side of the rudder-vertical fin than on the other. A yawing moment is the result which may be offset by use of a trimming tab or by offsetting the leading edge of the vertical fin. In multimotored aircraft, a large yawing moment is produced when one engine becomes dead. In such aircraft, the rudder control must be sufficiently effective to restore the balance. Provision by means of a flettner control to relieve the pilot of the strain of supplying a continuous control force to the rudder in order to maintain straight flight in cases of engine failure is becoming standard practise. The rudder control is considerably more effective at high speed than at low speed. In particular at speeds near the stall, the rudder control loses its effectiveness to a marked degree.

140. Lateral control.—The aileron control is most effective at high speed. As the stalling speed is approached the aileron control becomes sluggish. Accompanying the rolling effect of the ailerons is a yawing moment due to a redistribution of the drag on the wings. Moving the aileron down increases the drag on that wing, the resultant yaw causes the other wing to move faster tending to produce greater lift and consequent banking. This tendency operates against the normal aileron action and at stalling speeds may result in reversed aileron control action. The Frise balance now widely adopted for ailerons is so hinged that the nose of the lifted aileron drops below the wing surface and produces a drag on that wing. The tendency is to counterbalance the drag produced by the other aileron which is pulled down and thus counteract the tendency to reversal of the aileron control.

141. Autorotation.—At speeds less than the stalling speed the airplane becomes unstable laterally and the action of the aileron control is reversed. Any disturbance tending to increase the angle of attack on one wing decreases the lift on that wing causing a rolling moment. The increased angle of attack is accompanied by an increase in drag producing a yawing moment. The combined yawing and rolling motions result in a spin with the nose well down where equilibrium is established at a rate of descent and speed of rotation depending upon the characteristics of the airplane. Many

airplanes, if permitted to spin in the normal manner for a sufficient period of time, develop a flat spin. The immediate difference between the normal and the flat spin is the attitude of the airplane. Whereas the nose is pointed well down in the normal spin, with the preponderant motion one of roll, in the flat spin the nose approaches the horizon and the motion becomes one of nearly pure yaw. Airplanes having flat spin characteristics do not evidence them at the outset of the spin, but develop the flat spin from the normal spin. In the flat spin the aerodynamic forces on the elevators are very large and the control surfaces become largely ineffective. Recovery is always slow and difficult and frequently impossible.

142. Factors affecting spins.—An airplane must first be stalled before it will spin. Some airplanes will not spin for the reason that the elevator control is so ineffective that the airplane cannot be

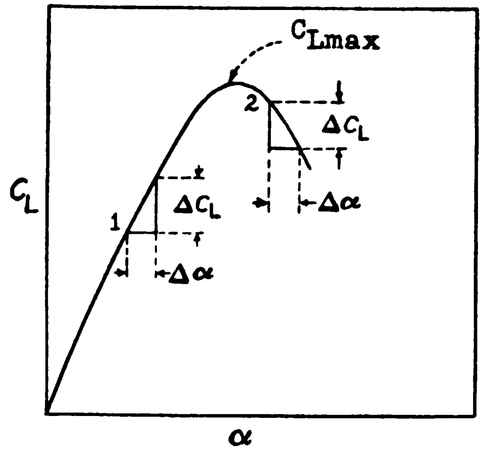


FIGURE 111.—Effect of change in angle of attack on lift below stall and beyond stall.

forced to a stalling angle of attack. By choice of wing section and the design and arrangement of gap, stagger, and decalage, the peak of the lift curve of the wing may be so flattened that spinning is difficult. The tendency of the airplane to spin depends upon the mass distribution, the shape of the wing structure, the position of the center of gravity, the area of the exposed fuselage, and the vertical tail group and its distance from the center of gravity. Since the flat spin occurs at angles of attack approaching 90°, the shape of the lift and drag curves at angles up to 90° may be expected to influence flat spinning tendencies and characteristics. Such has indeed proved to be the case.

143. Recovery from spins.—The National Advisory Committee for Aeronautics has made flight tests to study the spinning characteristics of various airplanes for a period of many years. For ex-

ample, over 900 spin tests were made with one airplane whose spinning characteristics were vicious at times due to modification in the load distribution. As a result of these tests, the conclusion was reached that no method of control manipulation for recovery from prolonged spins is infallible for all airplanes. Since dangerous spins develop from the normal spin, prolonged spinning should be prohibited. The following rules have been found generally applicable to recovery from spins:

a. During the spin before recovery is attempted, the ailerons should be neutral and the elevator and rudder controls should be held all the way with the spin.

b. When applying controls for recovery from a vicious spin, the rudder should be briskly moved to a position full against the spin and later, after at least one-half additional turn is made, the elevator should be moved to the full down position.

c. In a vicious spin, the applied controls should be held for at least five turns before attempting any other measure for promoting recovery.

144. Wing tip stalling.—*a.* The turbulent airflow that occurs when the wing stalls may not occur simultaneously at all points along the wing. The tapered wing now favored for cantilever monoplanes in many designs stalls very abruptly at the wing tip with consequent loss of aileron control. The use of the aileron to lift the dropping wing usually makes matters worse and spin develops rapidly unless the airplane is inherently stable against spinning.

b. The use of a considerable degree of static longitudinal stability, thus providing a definite warning of the approaching stall through the backward movement, position, and forces on the control column, together with a gradually developing stall secured by allowing the upper or lower wing of a biplane to stall first, or the use of monoplanes with little or no taper and "poor" wing-fuselage junctures which tend to bring about a gradually developing stall beginning at mid span are measures that insure that the stalled condition will develop progressively after a reasonably definite warning. Furthermore, these measures result in maintenance of lateral control owing to the fact that the essentially effective parts of the wing system remain unstalled even after the angle of attack has exceeded that of maximum lift.

c. Modern design trends toward high wing loadings and landing speeds; the use of efficient high speed airfoils having less desirable stalling characteristics; the use of highly tapered monoplane wings; the low wing position which contributes to reduced longitudinal sta-

bility; the use of "good" wing-fuselage junctures; and, finally, high lift devices add to the dangers of tip stalling and vicious section stalls resulting in sudden large and usually unsymmetrical loss of lift. The worst offenders may give no indication of the approaching stall which, when it occurs, is manifested by a sudden uncontrolled rolling dive, that results from a sudden loss of lift on one wing and a simultaneous loss of lateral control.

d. The airplane which stalls without warning is a menace in the hands of the less skillful pilot, and must be flown with such liberal margins of safety by even the most skillful pilot that full advantage cannot be taken of its performance characteristics.

SECTION VIII

DYNAMIC LOADS

145. Loads and load factors.—*a.* The *basic load* is the load on a structural member or part in any condition of static equilibrium of an airplane. It is the load due to the weight of the airplane in unaccelerated flight.

b. In accelerated flight, for each type of airplane, experience has indicated that the structure will be subjected to a load not in excess of a *maximum probable load*, also called *maximum applied load.* The limitations of the maximum applied load may be due to inherent flight characteristics of the airplane or may be due to prohibition of certain maneuvers in flight with the specific object of holding the maximum applied load to low limits. This ratio of the maximum applied load to the basic load is the *applied load factor.*

c. The necessity of keeping structural weight to a minimum requires the very close design of airplane parts and the elimination of all unnecessary material. To keep structural weight to a minimum, the parts are therefore designed to fail at an *ultimate load* which is customarily fixed at approximately 1.5 times the maximum applied load. The ratio of the ultimate load to the maximum applied load (usually about 1.5) is the *factor of safety.* This term as applied to airplane structures is not used in the same sense as used by the civil engineer in the design of bridges and similar structures, and its use in aeronautics results in much confusion and ambiguity.

d. The ratio of the ultimate load to the basic load is the *design load factor*. Since structural failure of aircraft is extremely hazardous to personnel and matériel, the design load factor must be large enough to eliminate structural failure if the airplane is flown within the limitations as to maneuvering placed on it by the regulations. Every case of structural failure is investigated, and where

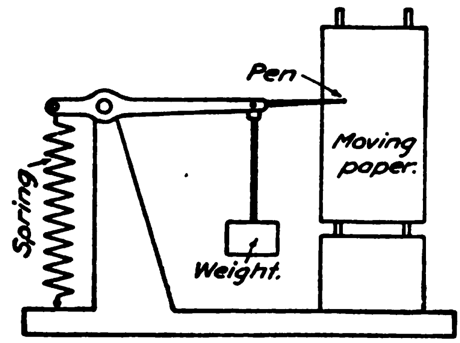


FIGURE 112.—Seismograph type of accelerometer.

repeated failure occurs during normal flying operations a revision in design load factors for subsequent types is in order.

146. Dynamic loads.—*a.* In flight, the dynamic loads which the wings carry depend upon accelerations which throw the airplane from its normal flight path. These accelerations may be due to sudden changes in air currents or to manipulation of the controls of

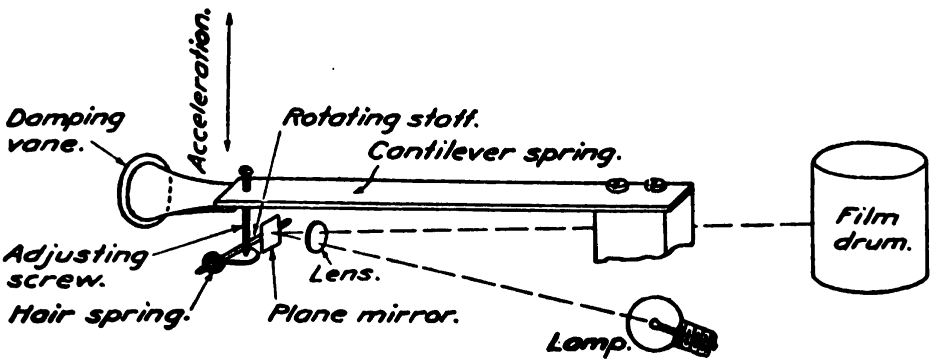


FIGURE 113.—Diagram of N. A. C. A. accelerometer.

the aircraft. Since acceleration is rate of change of velocity with time, very rapid changes result in large accelerations and large dynamic loads. Thus if a pilot pulls back on the control stick suddenly, the dynamic load imposed on the airplane will be greater than if he pulls back slowly. The pilot who performs maneuvers smoothly will stress the airplane structure less than the pilot who is addicted to rough erratic maneuvers. Similarly large aircraft which maneuver

slowly and for which loops, spins, rolls, and vertical dives are prohibited are subjected to lower dynamic loads than are small highly maneuverable aircraft designed for combat operations.

b. An accelerometer is an instrument which may be installed in an airplane for the purpose of recording the accelerations and hence the dynamic loads which occur in flight. The instrument is calibrated to read dynamic load factors, the dynamic load factor being unity in steady level flight. A form of accelerometer called the V–G recorder has been developed for the purpose of recording the maximum dynamic loads occurring on an airplane during the period of installation of the instrument. From this data a knowledge of proper load factors for future design may be obtained. The instrument also betrays the pilot who is inclined to perform prohibited maneuvers when unobserved.

147. Curvilinear flight.—In curvilinear motion the centrifugal force in pounds is

$$C.\ F. = \frac{W}{g} \times \frac{V^2}{r} \tag{91}$$

where W = the weight of the airplane in pounds
g = the acceleration of gravity
V = velocity of the airplane in ft./sec.
r = radius of curvature of the flight path in feet.

The centrifugal force is usually expressed as so many times the weight of the airplane. The greater the speed and the shorter the radius r the greater the centrifugal force.

In a perfectly executed turn, the angle of bank must be such that the vertical component of lift will equal the weight, and the horizontal component of lift will equal the centrifugal force. The sharper the turn the steeper the bank and the greater the dynamic load supported by the wings. The conditions for equilibrium are—

$$\begin{aligned} L_V &= W \\ L_H &= C.\ F. \\ L &= \sqrt{W^2 + C.\ F.^2} \end{aligned} \tag{92}$$

148. Accelerations due to sudden change in angle of attack.—When an airplane encounters a gust, the vertical component of the gust produces a sudden change in angle of attack. Should the change occur so that the angle of attack of maximum lift is suddenly reached, the forces acting on the wings will be

$$\text{Lift on wings} = F = C_{L\max}\, \rho/2\, SV^2 \tag{93}$$

where V is the original speed of flight.

When in steady flight at maximum C_L

$$\text{Weight} = C_{L\max}\,\rho/2\,SV^2_{\min} \tag{94}$$

Dividing equation 93 by equation 94.

$$\frac{F}{W} = \frac{V^2}{(V_{\min})^2} \tag{95}$$

The ratio F/W is the dynamic load factor in terms of g, and it will be observed the higher the velocity of flight V the greater are the possible dynamic loads due to gusts.

Rapid changes in angle of attack may be also secured by sudden movement of the elevator control. The dynamic loads produced are of the same nature as those resulting from the action of gusts in changing angle of attack. The maximum accelerations are the result

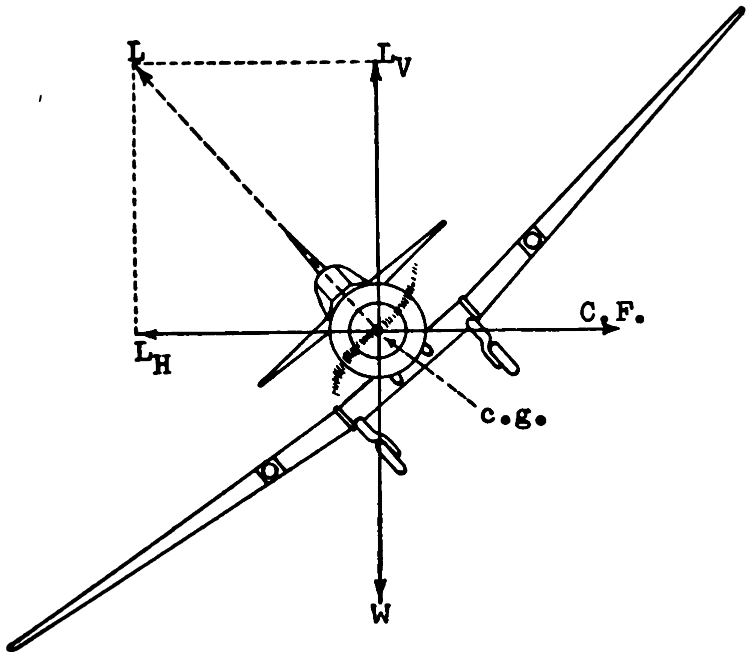


FIGURE 114.—Curvilinear flight.

of a sudden pull up from a steep dive. Theoretically, the maximum possible dynamic load factor is the ratio $\left(\frac{V_T}{V_{\min}}\right)^2$, where V_T is terminal velocity in a dive and $V_{\min}$ the speed of flight at $C_{L\max}$ (landing speed).

Actually, the theoretical maximum dynamic loads are never attained. Gusts do not develop instantaneously and the pull up from a dive occurs over an interval of time such that the velocity of flight has dropped before the angle of attack of $C_{L\max}$ can be reached.

The probable loads due to gusts and the gust load factors for design purposes are based on the assumption of a sharp-edged gust

with an intensity of 30 feet per second acting in either direction normal to the flight path and at all velocities up to the maximum permissible diving speed. The structural failures that have resulted during flight in the turbulent air conditions of violent thunderstorms indicate that the gusts encountered in such meteorological conditions may impose greater loads on the aircraft structure than can be accounted for by the assumed 30 feet per second gust.

The ratio of the maximum speed in horizontal flight to the minimum speed (landing speed) is defined as the speed range. The square of the speed range is the theoretical maximum dynamic load at the maximum speed of flight. Airplanes with high parasite

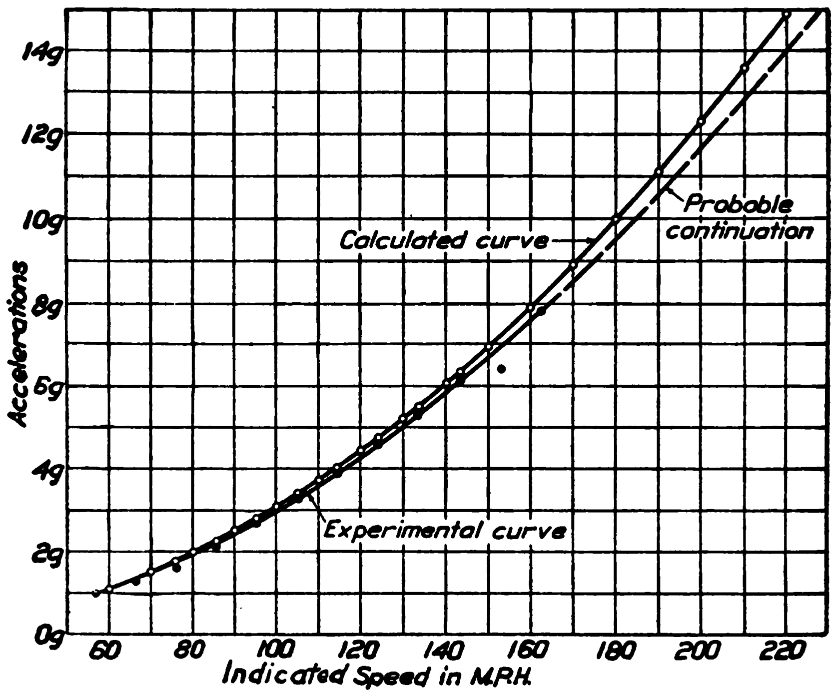


FIGURE 115.—Curves showing theoretical and actual wing loads on pursuit airplane.

resistance and low speed range therefore are subjected to lower dynamic load factors than airplanes of clean design with low parasite resistance and high speed range.

The load factors imposed during maneuvers (maneuver load factors) are proportional to the square of the speed at the start of the maneuver (equation 95) where the angle of attack of maximum lift is reached instantaneously. Only in small highly maneuverable airplanes of the pursuit type is it possible to impose approximately the theoretical maximum load in a maneuver. Figure 115 shows the loads resulting from the rapid pull up from a dive of a pursuit airplane at various airspeeds. In all airplanes other than the pursuit

type, the magnitude of the control forces required and the slower maneuverability characteristics combine to increase the spread between the actual maneuver load factors and those theoretically possible.

149. Aerodynamic loads.—*a.* Generally speaking, there are two ways in which a pilot may increase the applied aerodynamic loads on an airplane in flight:

(1) *By increasing angle of attack without change in airspeed.*—In this maneuver, the most significant change of applied load is an increase in the component of total wing force acting normal to the axis of the airplane, and the effect of this increase in normal force is to produce an acceleration of the airplane in the normal direction. This normal acceleration is usually expressed as a ratio to the acceleration of gravity.

(2) *By increasing airspeed.*—The second determinant of applied load, airspeed, produces simultaneous change in both the lift and the drag forces. If, as is the usual case, an airplane is maneuvered so as to experience the change in airspeed with negligible change in applied normal force, the applied drag load still is subject to variation as the airspeed is altered. But there are other consequences of airspeed change which are of even greater importance than drag forces, and these less obvious effects are caused not so much by change in the magnitude of the applied loads as by shift in their distribution over the airplane. Thus, although a steady high speed glide or dive is characterized by a small resultant applied normal force, the wing torsion, the tail load, and the resultant bending moment and shear carried by the fuselage reach exceedingly large values in this maneuver. Normal acceleration and indicated airspeed are the two fundamental criteria which determine the external loads applied to the primary structure of any given airplane in flight. The limitation of normal acceleration (load factor) and airspeed which the airplane should be capable of withstanding without permanent deformation of any structural member are prescribed as a preliminary to the design of every new airplane.

b. Obviously, the selection of load factors as well as maximum permissible diving speed depend upon the type of service for which the airplane is intended. The positive and negative applied load factors and the maximum diving speeds of the various types of Air Corps airplanes are designed so that no structural part is stressed beyond the point where permanent deformation will occur. The design load factors are 50 percent greater than the maneuver load factors and represent the point at which total failure of the structure may be expected to occur.

150. V–G diagram.—*a*. The limiting load factors and diving speeds are very conveniently shown on the graphical chart known as a V–G (velocity-acceleration) diagram, a typical one of which is presented in figure 116. Taking the type BT "basic training" airplane as the example, the positive and negative maneuver load factors of plus 5.67 and minus 2.33 are represented by the lines *AB* and *DC*. These maneuver load factor lines are drawn horizontally because it is an Air Corps requirement that all airplanes be able to sustain the same given maximum value of applied load factor throughout the permissible range of airspeed. The high speed of the BT in level flight is 174 miles per hour and is identified on this diagram by the dashed line, *HH'*. The maximum permissible diving speed for this airplane is 130 percent of 174, or 226 miles per hour, and is represented by the line *BC* in figure 116. The curved lines *OA* and *OD* are based upon aerodynamic rather than structural considerations, and they define the maximum positive and negative accelerations which it is possible to attain at various speeds with the fully loaded BT operating at its maximum positive and negative lift coefficients, respectively. Thus point *A* occurs at the lowest value of indicated airspeed at which it is theoretically possible to reach the maximum allowable positive load factor of 5.67; and, similarly, point *D* marks the airspeed below which the maximum negative load factor of minus 2.33 cannot be reached.

b. The closed boundary *OABCDO* has been drawn in such a manner as to include the full range of airspeed and applied load factor which the Air Corps requires that this airplane be capable of withstanding with complete safety. But, before these limiting flight conditions can be approved as a basis for structural design, it is necessary to determine whether or not the airplane would be in danger of experiencing an excessive acceleration if flown at high speed in a region of gusty or "bumpy" air.

c. Assuming that the maximum gust velocities encountered in flight are 30 feet per second, it may be shown that for horizontal flight—

$$n=1\pm\frac{3.0mV}{W/S} \qquad (96)$$

and for the vertical dive—

$$n=\pm\frac{3.0mV}{W/S} \qquad (97)$$

Where

n=normal acceleration in g units (load factor)

m=slope of the airplane normal force coefficient *vs.* angle of attack curve in absolute units per degree.

V=calibrated airspeed in miles per hour.

W=airplane gross weight in pounds.
S=wing area in square feet.
The equation 96, plotted for the BT, is shown by the lines *KP* and *KQ* in figure 116, and equation 97 is expressed by lines *OM* and *ON*.

d. It will be noted that the first mentioned gust lines, *KP* and *KQ* most nearly represent the conditions which prevail in steady flight

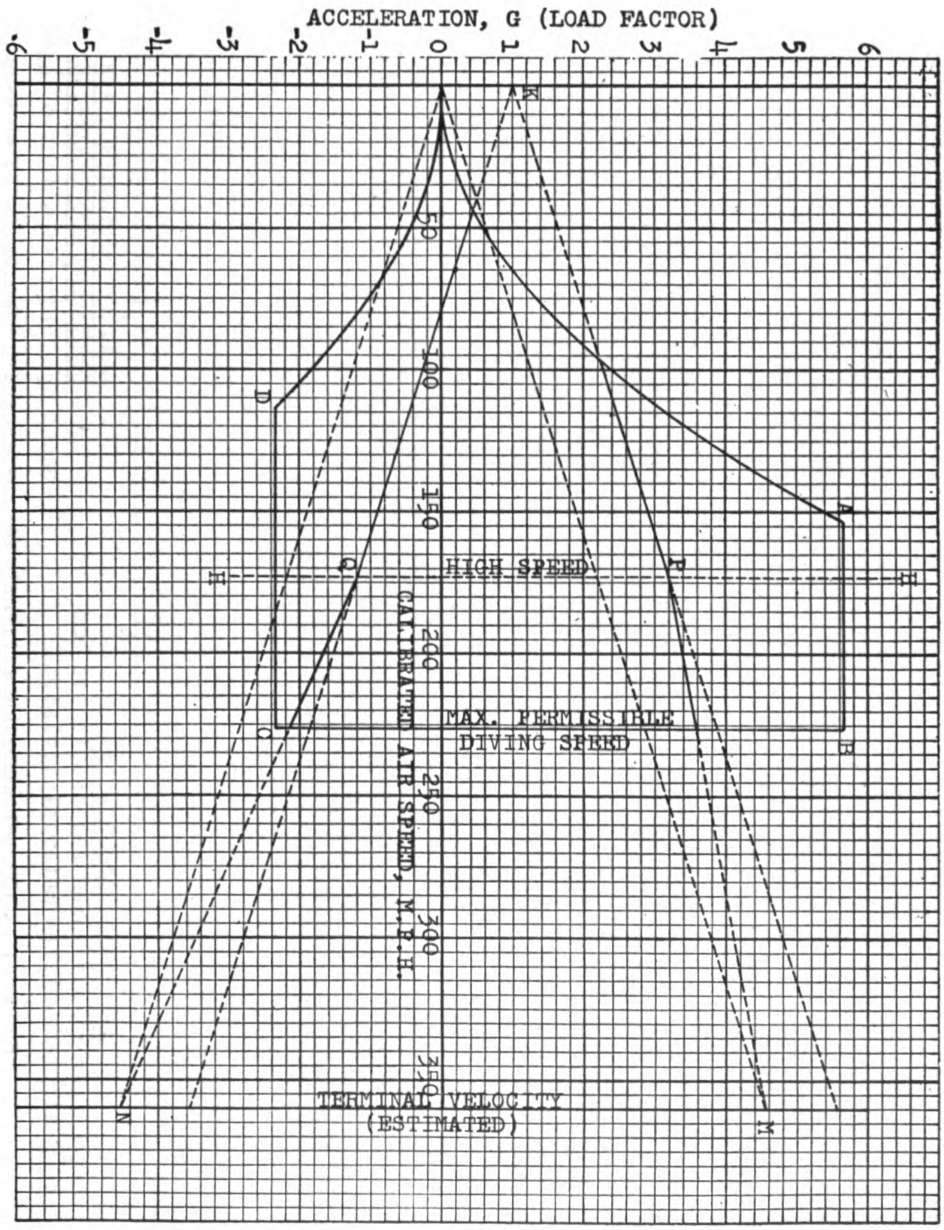


FIGURE 116.—V-G diagram for BT airplane based on gross weight of 4,400 pounds.

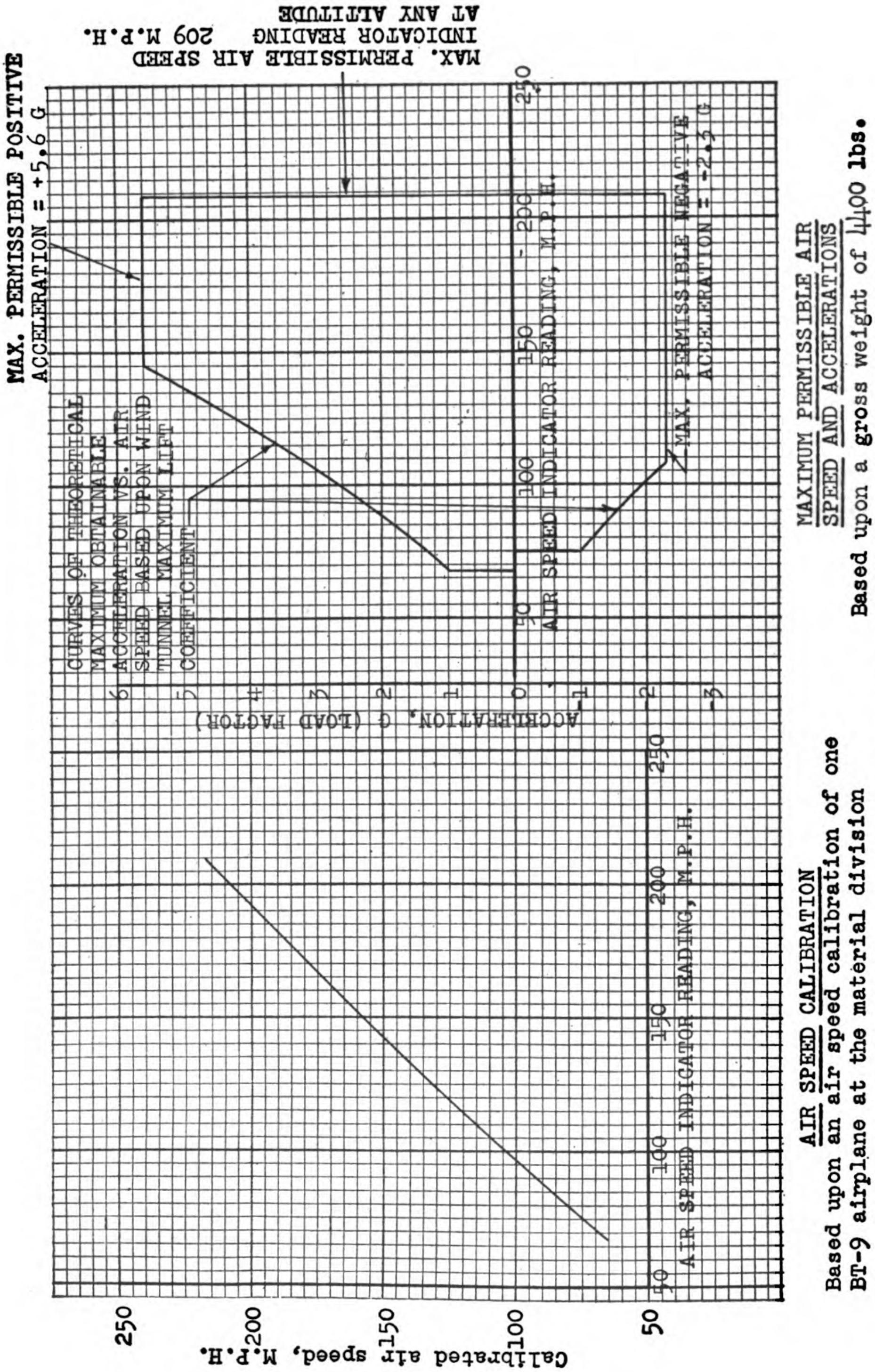


FIGURE 117.—Airspeed calibration and permissible airspeed and acceleration for BT airplane.

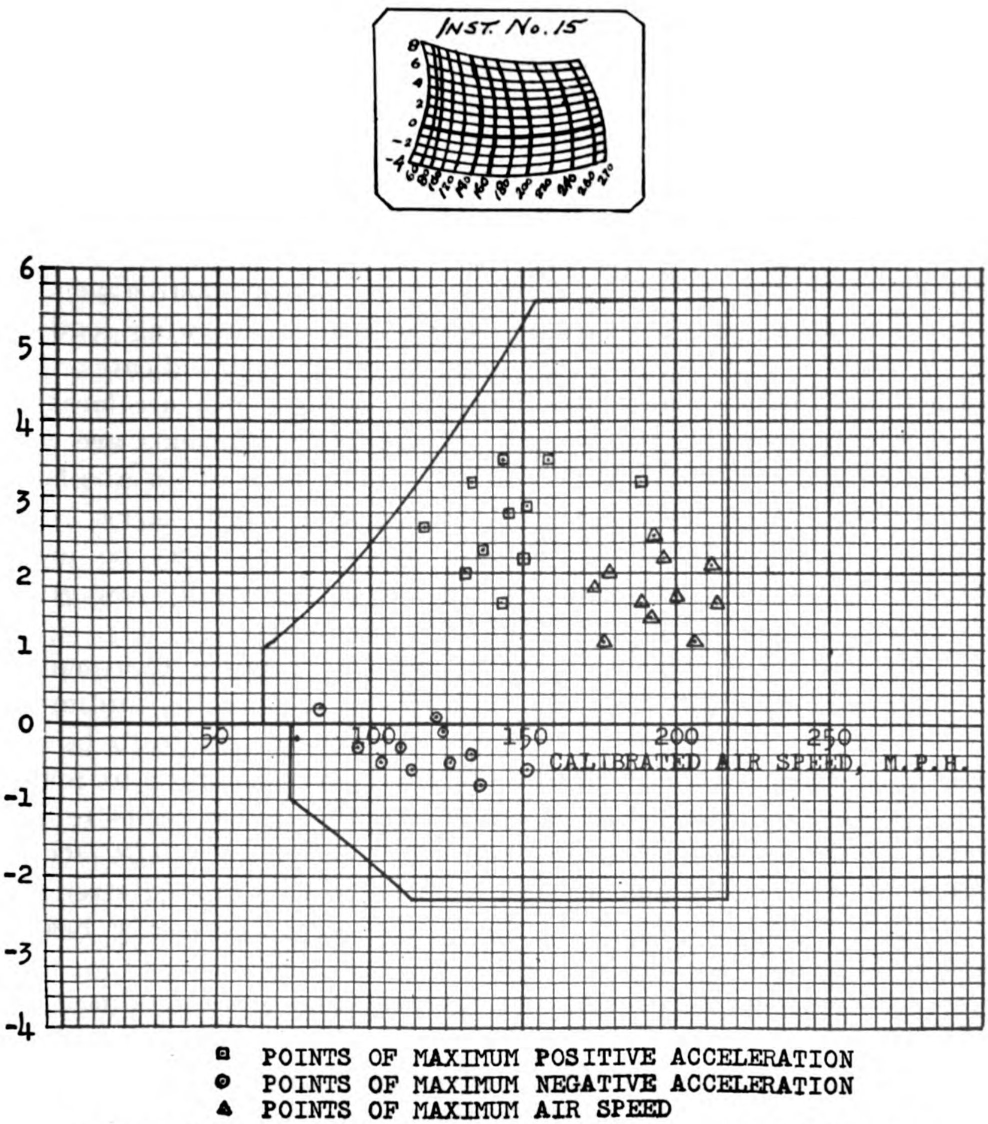


FIGURE 118.—Typical plot of peak readings from V-G records of BT airplane.

at speeds up to and including the high speed for level flight. The lines *OM* and *ON* have no real significance except at the terminal velocity which is the only steady flight condition attainable in the vertical attitude. Between level flight at high speed and the terminal velocities, it is assumed arbitrarily that the attitude of the airplane changes from horizontal to vertical in a manner such that the applied gust load factors over this range in speed can be expressed by the straight lines *PM* and *QN*. The maximum applied gust load factors through the entire speed range of the BT airplane are represented by the lines *KPN* for positive gusts and by the lines *KQM* for negative gusts.

e. Inspection of the V-G diagram shows that, within the permissible range of airspeed for this airplane, all positive and negative gust load factors are within the corresponding maximum safe limits of plus 5.67 and minus 2.33. Therefore, the gusts are not critical for this airplane and no account need be taken of them in designing the structure for the full-loaded gross weight condition. From equation 96 it is evident that the increment of load factor due to a vertical gust of given velocity is inversely proportional to the wing loading at the time of encountering the gust, and this fact indicates that an airplane lightly loaded is subjected to greater gust acceleration than when at normal gross weight. These latter comments are presented merely to show that certain structural parts of an airplane, particularly motor mounts and other members which carry loads that are independent of the airplane gross weight, may be overstressed by excessive gust accelerations due to abnormally low gross weight.

f. Evidently the limiting accelerations and airspeed represented in figure 116 by lines *AB*, *DC*, and *BC* are at once the minimum values for design purposes and the maximum safe limits to be attained in flight. Thus, it is the designer's responsibility to make the BT airplane capable of withstanding all applied loads represented by the V-G points included in the configuration *OABCDO* in figure 116, but he is under no obligation to provide greater strength than this because to do so would require an unnecessarily heavy structure.

g. The essential features of the V-G diagram are reproduced in slightly different form on the operating chart in figure 117, which is issued for the information of all personnel flying airplanes of the BT series. For simplicity of application, airspeeds specified in figure 117 are "airspeed indicator reading" and an airspeed calibration curve for the BT airplane is presented in order that indicator readings may be converted to calibrated airspeed if desired. A diagram of

this kind may be prepared for each new type of airplane. It will be noted that the permissible high speed given in figure 117 is somewhat lower than the corresponding value which appears on the V-G diagram of figure 116, and this added margin of safety is provided to allow for calibration differences.

h. In certain instances it becomes necessary in view of demonstrated structural deficiencies, to issue special flight restrictions. Such action is not taken unless clearly warranted, and it is of the utmost importance that all special restrictions of this kind be carefully observed.

151. V-G Recorder.—The V-G recorder developed by the N. A. C. A. records on the smoked surface of a small glass plate variations of airspeed and of normal acceleration. The airspeed is recorded as the abscissa and the load factor as the ordinate, so that each point on the smoked glass record corresponds to a similar point on a V-G diagram such as that in figure 116. The plot of the peak readings from a large number of V-G records obtained from instruments installed in BT airplanes is shown in figure 118.

a. For several years the Air Corps, with the full cooperation of the National Advisory Committee for Aeronautics, has used the N. A. C. A. V-G recorder in a study of velocity-acceleration conditions imposed upon service airplanes of various types, and this investigation has been expanded to the extent that there now are about 80 of these instruments in use at principal Air Corps stations throughout the United States. Ordinarily, the recorders are assigned to representative airplanes of the newer types. Record glasses, changed at monthly intervals, are forwarded to the Matériel Division for evaluation and compilation of results. Altogether, more than 1,300 of these records, covering over 46,000 flight hours and representing every type of airplane, have been obtained.

b. The maximum values of speeds and the acceleration are plotted on charts similar to that in figure 118, which affords a convenient representation of the data according to airplane type. Any excess of airspeed or acceleration is readily apparent from these charts and each such case is brought to the attention of the proper authorities. Over a period of the past 2 years a study of the results obtained from the records of the V-G recorder indicate that very rarely are excessive load factors imposed, but that very frequently permissible diving speeds are exceeded. Every pilot should realize that modern aircraft of clean design attain high diving speeds very quickly and that when the diving speed exceeds the permissible safe limit, the risk of dangerous structural failure is very great.

APPENDIX

NOMENCLATURE

The National Advisory Committee on Aeronautics from time to time publishes reports for the purpose of encouraging greater uniformity and precision in the use of terms relative to aeronautics. Report No. 474, 1933, was prepared by a special conference on aeronautical nomenclature which was attended by representatives of the Army Air Corps, Navy Bureau of Aeronautics, Bureau of Standards, and Aeronautics Branch, Department of Commerce. In some cases the definitions adopted in the N. A. C. A. Report No. 474 have not been entirely satisfactory to the Matériel Division, Air Corps. The definitions that follow have been extracted from Report 474 and modified or supplemented to conform to the practice of the Matériel Division.

Accelerometer.—An instrument that measures the accelerations of an aircraft in the defined direction.

Aerodynamic center, wing section.—A point located on or near the chord of the mean line approximately one-quarter of the chord length aft of the leading edge and about which the moment coefficient is practically constant.

Aerodynamics.—The branch of dynamics that treats of the motion of air and other gaseous fluids and of the forces acting on solids in motion relative to such fluids.

Aeronautics.—The science and art of flight.

Aerostatics.—The science that treats of the equilibrium of gaseous fluids and of bodies immersed in them.

Aileron.—A hinged or movable portion of an airplane wing, the primary function of which is to impress a rolling motion on the airplane. It is usually part of the trailing edge of a wing.

Aircraft.—Any weight-carrying device designed to be supported by the air, either by buoyancy or by dynamic action.

Airfoil.—Any surface, such as an airplane wing, aileron, or rudder, designed to obtain reaction from the air through which it moves.

Airfoil profile.—The outline of an airfoil section.

Airfoil section.—A cross section of an airfoil parallel to the plane of symmetry or to a specified reference plane.

Airplane.—A mechanically driven fixed-wing aircraft, heavier than-air, which is supported by the dynamic reaction of the air against its wings.

Airspeed.—The speed of an aircraft relative to the air.

Airspeed head.—An instrument which, in combination with a gage, is used to measure the speed of an aircraft relative to the air. It usually consists of a pitot-static tube or a pitot-venturi tube.

Altitude, absolute.—The height of an aircraft above the earth.

Altitude, critical.—The maximum altitude at which a supercharger will develop normal rated manifold pressure at normal rated r. p. m. under standard altitude conditions.

Altitude, density.—The altitude corresponding to a given density in a standard atmosphere.

Altitude, pressure.

The altitude corresponding to a given pressure in a standard atmosphere.

The altitude at which the gas bags of an airship become full.

Amphibian.—An airplane designed to rise from and alight on either land or water.

Angle, aileron.—The angular displacement of an aileron from its neutral position. It is positive when the trailing edge of the aileron is below the neutral position.

Angle, blade.—The acute angle between the chord of a section of a propeller, or of a rotary wing system, and a plane perpendicular to the axis of rotation.

Angle, dihedral.—The acute angle between a line perpendicular to the plane of symmetry and the projection of the leading edge of the wing reference chords on a plane perpendicular to the longitudinal reference axis of the airplane.

Angle, downwash.—The angle through which an airstream is deflected by any lifting surface. It is measured in a plane parallel to the plane of symmetry.

Angle, drift.—The horizontal angle between the longitudinal axis of an aircraft and its path relative to the ground.

Angle, elevator.—The angular displacement of the elevator from its neutral position. It is positive when the trailing edge of the elevator is below the neutral position.

Angle, flight-path.—The angle between the flight path of the aircraft and the horizontal.

Angle, gliding.—The angle between the flight path during a glide and a horizontal axis fixed relative to the air.

Angle, zero-lift.—The angle of attack of an airfoil when its lift is zero.

Angle of attack.—The acute angle between a reference line in a body and the line of the relative wind direction projected on a plane containing the reference line and parallel to the plane of symmetry.

Angle of attack, absolute.—The angle of attack of an airfoil, measured from the attitude of zero lift.

Angle of attack, critical.—The angle of attack at which the flow about an airfoil changes abruptly as shown by corresponding abrupt changes in the lift and drag.

Angle of attack for infinite aspect ratio.—The angle of attack at which an airfoil produces a given lift coefficient in a two-dimensional flow. Also called "effective angle of attack".

Angle of incidence.—Same as *Angle of wing setting.* In British terminology the angle of incidence is equivalent to the American term "angle of attack".

Angle of pitch (aircraft).—The acute angle between two planes defined as follows: One plane includes the lateral axis of the aircraft and the direction of the relative wind; the other plane includes the lateral axis and the longitudinal axis. The angle is positive when the nose of the aircraft is above the direction of the relative wind. (In normal flight the angle of pitch is the angle between the longitudinal axis and the direction of the relative wind.)

Angle of roll (or angle of bank).—The angle through which an aircraft must be rotated about its longitudinal axis in order to bring its lateral axis into the horizontal plane. The angle is positive when the left side is higher than the right.

Angle of stabilizer setting.—The acute angle between the longitudinal axis of an airplane and the chord of the stabilizer. The angle is positive when the leading edge is higher than the trailing edge.

Angle of wing setting.—The acute angle between the plane of the wing chord and the longitudinal axis of the airplane. The angle is positive when the leading edge is higher than the trailing edge.

Angle of yaw.—The acute angle between the direction of the relative wind and the plane of symmetry of an aircraft. The angle is positive when the aircraft turns to the right.

Area, equivalent flat-plate.—The area of a square flat plate, normal to the direction of motion, which offers the same amount of resistance to motion as the body or combination of bodies under consideration.

Area, wing.—Wing area is measured from the projection of the actual outline on the plane of the chords, without deduction for area blanketed by fuselage or nacelles. That part of the area, so determined, which lies within the fuselage or nacelles is bounded by two lateral lines that connect the intersections of the leading and trailing edges with the fuselage or nacelle, ignoring fairings

and fillets. For the purpose of calculating area, a wing is considered to extend without interruption through the fuselage and nacelles. Unless otherwise stated, wing area always refers to total area including ailerons.

Aspect ratio.—The ratio of the span to the mean chord of an airfoil; that is, the ratio of the square of the span to the total area of an airfoil.

Atmosphere: Altimeter-calibration standard atmosphere.—A standard atmosphere used in calibrating aeronautic instruments. The standard now in use in the United States is completely defined in N. A. C. A. Report No. 246.

Atmosphere, standard.—An arbitrary atmosphere used in comparing the performance of aircraft. The standard atmosphere in use in the United States at present represents very nearly the average conditions found at latitude 40° and is completely defined in N. A. C. A. Report No. 218.

Atmosphere, standard international.—The atmosphere used as an international standard presumes for mean sea level and a temperature of 15° C. a pressure of 1,013.2 millibars, lapse rate of 6.5° per kilometer from sea level to 11 kilometers, and thereafter a constant temperature of −56.5° C.

Balance.—A condition of steady flight in which the resultant force and moment on the airplane are zero.

Balanced surface: aerodynamic balanced surface.—A control surface that extends on both sides of the axis of the hinge or pivot or that has auxiliary devices or extensions connected with it in such a manner as to effect a small or zero resultant moment of the air forces about the hinge axis.

Balanced surface, static.—A control surface whose center of mass is in the hinge axis.

Bank.—The position of an airplane when its lateral axis is inclined to the horizontal. A right bank is the position with the lateral axis inclined downward to the right.

Bank.—To incline an airplane laterally; that is, to rotate it about its longitudinal axis.

Biplane.—An airplane with two main supporting surfaces placed one above the other.

Blade back.—The side of a propeller blade that corresponds to the upper surface of an airfoil.

Blade element.—A portion of a propeller blade contained between the surface of two cylinders coaxial with the propeller, cutting the propeller blades.

Blade face.—The surface of a propeller blade that corresponds to the lower surface of an airfoil. Sometimes called "thrust face" or "driving face".

Blade section.—A cross section of a propeller blade made at any point by a plane parallel to the axis of rotation of the propeller and tangent at the centroid of the section to an arc drawn with the axis of rotation as its center.

Boundary layer.—A layer of fluid, close to the surface of a body placed in a moving stream, in which the impact pressure is reduced as a result of the viscosity of the fluid.

Buffeting.—Buffeting is the intermittent application of aerodynamic forces to a part of an aircraft, caused and maintained by unsteady flow from a turbulence set up by any other part of the aircraft.

Burble.—A term designating the breakdown of the streamline flow about a body.

Cabane.—An arrangement of struts used for bracing on an aircraft.

Camber.—The rise of the curve of an airfoil section, usually expressed as the ratio of the departure of the curve from a straight line joining the extremities of the curve to the length of this straight line. "Upper camber" refers to the upper surface; "lower camber" to the lower surface; and "mean camber" to the mean line of the section. Camber is positive when the departure is upward, and negative when it is downward.

Ceiling, absolute.—The maximum height above sea level at which a given airplane would be able to maintain horizontal flight under standard air conditions.

Ceiling, service.—The height above sea level, under standard air conditions, at which a given airplane is unable to climb faster than a small specified rate (100 feet per minute in the United States and England). This specified rate may differ in different countries.

Center of airfoil moments.—The point about which the basic airfoil moment coefficients are given, usually the aerodynamic center of ¼ of the mean aerodynamic chord.

Center of gravity.—Usually refers to the center of gravity of the airplane fully loaded. Sometimes used for the center of gravity of a single load or a special set of loads, in which case the load or loads concerned should be stated or clearly implied by the context.

Center of pressure of an airfoil.—The point in the chord of an airfoil, prolonged if necessary, which is at the intersection of the chord and the line of action of the resultant air force.

Center of pressure coefficient.—The ratio of the distance of the center of pressure from the leading edge to the chord length.

Chandelle.—An abrupt climbing turn to approximately a stall in which the momentum of the airplane is used to obtain a higher rate of climb than would be possible in unaccelerated flight. The purpose of this maneuver is to gain altitude at the same time that the direction of flight is changed.

Chord.—An arbitrary datum line from which the ordinates and angles of an airfoil are measured. It is usually the straight line tangent to the lowest surface at two points, the straight line joining the ends of the mean line, or the straight line between the leading and trailing edges.

Chord, mean aerodynamic.—The chord of an imaginary airfoil which would have force vectors throughout the flight range identical with those of the actual wing or wings.

Chord, mean of a wing.—The chord of an imaginary airfoil area by the span.

Chord length.—The length of the projection of the airfoil profile on its chord.

Cockpit.—An open space in an airplane for the accommodation of pilots or passengers. When completely enclosed, such a space is usually called a cabin.

Controllability.—The quality of an aircraft that determines the ease of operating its controls and/or the effectiveness of displacement of the controls in producing change in its attitude in flight.

Controls.—A general term applied to the means provided to enable the pilot to control the speed, direction of flight, attitude, power, etc., of an aircraft.

Control surface.—A movable airfoil designed to be rotated or otherwise moved by the pilot in order to change the attitude of the aircraft.

Cowling.—A removable covering.

Cowling, cockpit.—A metal or plywood cowling placed around a cockpit.

Cowling, engine.—A romovable covering placed around all or part of an airplane engine.

Cowling, N. A. C. A.—A cowling enclosing a radial air-cooled engine, consisting of a hood, or ring, and a portion of the body behind the engine so arranged that the cooling air smoothly enters the hood at the front and leaves through a smooth annular slot between the body and the rear of the hood; the whole forming a relatively low-drag body with a passage through a portion of it for the cooling air.

Decalage.—The difference between the angular settings of the wings of a biplane. The decalage is measured by the acute angle between the zero-lift chords in the plane of symmetry and is considered positive if the chords converge ahead of the wings.

NOTE.—The sign of decalage in N. A. C. A. report No. 474 is negative for this condition.

Dive.—A steep descent, with or without power, in which the airspeed is greater than the maximum speed in horizontal flight.

Downwash.—The air deflected perpendicular to the direction of motion of an airfoil.

Drag.—The component of the total air force on a body parallel to the relative wind.

Drag, induced.—That part of the drag induced by the lift.

Drag, parasite.—The total drag of an aircraft minus the total wing drag.

Drag, profile.—The difference between the total wing drag and the induced drag.

Dynamic factor (stress analysis).—The ratio between the load carried by any part of an aircraft when accelerating and the corresponding basic load.

Dynamic pressure.—The product $\frac{1}{2}\rho V^2$, where ρ is the density of the air and V is the relative speed of the air.

Elevator.—A movable auxiliary airfoil, the function of which is to impress a pitching moment on the aircraft. It is usually hinged to the stabilizer.

Equivalent monoplane.—A monoplane wing equivalent as to its lift and drag properties to any combination of two or more wings.

Factor of safety.—The ratio of the design load or the ultimate load to the maximum applied load. In airplane design the least factor of safety is usually 1.5.

Fairing.—An auxiliary member or structure whose primary function is to reduce the drag of the part to which it is fitted.

Fin.—A fixed or adjustable airfoil, attached to an aircraft approximately parallel to the plane of symmetry, to afford directional stability; for example, tail fin, skid fin, etc.

Fineness ratio.—The ratio of the length to the maximum diameter of a streamline body, as an airship hull.

Flap.—A hinged or pivotal airfoil forming the rear portion of an airfoil, used to vary the effective camber.

Flight path.—The flight path of the center of gravity of an aircraft with reference to the earth, or with reference to a frame fixed relative to the air.

Flow, laminar.—A particular type of streamline flow. The term is usually applied to the flow of a viscous liquid near solid boundaries, when the flow is not turbulent.

Flow, streamline.—A fluid flow in which the streamlines, except those very near a body and in a narrow wake, do not change with time.

Flow, turbulent.—Any part of a fluid flow in which the velocity at a given point varies more or less rapidly in magnitude and direction with time.

Flutter.—An oscillation of definite period set up in any part of an aircraft by a momentary disturbance, and maintained by a combination of the aerodynamic, inertia, and elastic characteristics of the member itself, which characteristics govern the nature of the flutter, that is, destructive, steady, or diminishing.

Fuselage.—The body, of approximately streamline form, to which the wings and tail unit of an airplane are attached.

Fuselage, monocoque.—A fuselage construction which relies on the strength of the skin or shell to carry either the shear or the load due to bending moments.

Gap.—The distance separating two adjacent wings of a multiplane.

Glide.—To descend at a normal angle of attack with little or no thrust.

Helicopter.—A type of rotor plane whose support in the air is normally derived from airfoils mechanically rotated about an approximately vertical axis.

Impact pressure.—The pressure acting at the forward stagnation point of a body, such as a pitot tube, placed in an air current. Impact pressure may be measured from an arbitrary datum pressure.

Landing gear.—The understructure which supports the weight of an aircraft when in contact with the land or water and which usually contains a mechanism for reducing the shock of landing. Also called "undercarriage".

Landing gear, retractable.—A type of landing gear which may be withdrawn into the body or wings of an airplane while it is in flight, in order to reduce the parasite drag.

Leading edge.—The foremost edge of an airfoil or propeller blade.

Lift/Drag ratio.—The ratio of the lift to the drag of any body.

Load, basic (stress analysis).—The load on a structural member or part in any condition of static equilibrium of an airplane. When a specific basic load is meant, the particular condition of equilibrum must be indicated in the context.

Load, design (stress analysis).—The load for which a member is designed. It is usually obtained by multiplying a basic load by a specified design load factor.

Load, ultimate (stress analysis).—The load that causes destructive failure in a member during a strength test, or the load that, according to computations, should cause destructive failure in the member.

Load factor (stress analysis).—The ratio of two loads (the second being a basic load) that have the same relative distribution. The first load may be the load applied during some special maneuver, the maximum probable load on the airplane or part, the design load, or the ultimate load. Whenever a load factor is mentioned, the context should indicate clearly what load is being compared with the basic load. If the context does not so indicate, the load factor is usually the ratio of the design load to the weight of the airplane.

Loading, power.—The gross weight of an airplane divided by the rated horsepower of the engine computed for air of standard density, unless otherwise stated.

Loading, wing.—The gross weight of an airplane divided by the wing area.

Loop.—A maneuver executed in such a manner that the airplane follows a closed curve approximately in a vertical plane.

Maneuverability.—That quality in an aircraft which determines the rate at which its attitude and direction of flight can be changed.

Monoplane.—An airplane with but one main supporting surface, sometimes divided into two parts by the fuselage.

Monoplane, high-wing.—A monoplane in which the wing is located at or near the top of the fuselage.

Monoplane, low-wing.—A monoplane in which the wing is located at or near the bottom of the fuselage.

Monoplane, midwing.—A monoplane in which the wing is located approximately midway between the top and bottom of the fuselage.

Monoplane, parasol.—A monoplane in which the wing is above the fuselage.

Nacelle.—An enclosed shelter for personnel or for a power plant. A nacelle is usually shorter than a fuselage, and does not carry the tail unit.

Nose-heavy.—The condition of an airplane in which the nose tends to sink when the longitudinal control is released in any given attitude of normal flight (*see also* Tail-heavy).

Oscillation, phugoid.—A long-period oscillation characteristic of the disturbed longitudinal motion of an aircraft.

Oscillation, stable.—An oscillation whose amplitude does not increase.

Oscillation, unstable.—An oscillation whose amplitude increases continuously until an attitude is reached from which there is no tendency to return toward the original attitude, the motion becoming a steady divergence.

Overhang.—

a. One-half the difference in span of any two main supporting surfaces of an airplane. The overhang is positive when the upper of the two main supporting surfaces has the larger span.

b. The distance from the outer strut attachment to the tip of a wing.

Pitch (or pitching) indicator.—An instrument for indicating the existence and approximate magnitude of the angular velocity about the lateral axis of an aircraft.

Pitch of a propeller.—*a. Effective pitch.*—The distance an aircraft advances along its flight path for one revolution of the propeller.

Geometrical pitch.—The distance an element of a propeller would advance in one revolution if it were moving along a helix having an angle equal to its blade angle.

Zero-thrust pitch.—The distance a propellor would have to advance in one revolution to give no thrust. Also called "experimental mean pitch."

Pitch ratio (propeller).—The ratio of the pitch to the diameter.

Pitot-static tube.—A parallel or coaxial combination of a pitot and a static tube. The difference between the impact pressure and the static pressure is a function of the velocity of flow past the tube.

Pitot tube.—A cylindrical tube with an open end pointed upstream, used in measuring impact pressure.

Pitot-venturi tube.—A combination of a pitot and a venturi tube.

Profile thickness.—The maximum distance between the upper and lower contours of an airfoil, measured perpendicularly to the mean line of the profile.

Propeller thrust.—The component of the total air force on the propeller which is parallel to the direction of advance.

Propeller thrust, static.—The thrust developed by a propeller when rotating without translation.

Range, maximum.—The maximum distance a given aircraft can cover, under given conditions, by flying at the economical speed and altitude at all stages of the flight.

Reynold's number.—A nondimensional coefficient used as a measure of the dynamic scale of a flow. Its usual form is the fraction $\rho \frac{Vl}{\mu}$

in which ρ is the density of the fluid, V is the velocity of the fluid, 1 is a linear dimension of the body in the fluid, and μ is the coefficient of viscosity of the fluid (*see also* Scale effect).

Roll.—An angular displacement about an axis parallel to the longitudinal axis of an aircraft.

Rudder.—A hinged or movable auxiliary airfoil on an aircraft, the function of which is to impress a yawing moment on the aircraft.

Scale effect.—The change in any force coefficient, such as the drag coefficient, due to a change in the value of Reynold's number.

Separation.—The phenomenon in which the flow past a body placed in a moving stream of fluid separates from the surface of the body.

Sideslipping.—Motion of an aircraft relative to the air, in which the lateral axis is inclined and the airplane has a velocity component along the lateral axis. When it occurs in connection with a turn, it is the opposite of skidding.

Skidding.—Sliding sidewise away from the center of curvature when turning. It is caused by banking insufficiently, and is the opposite of sideslipping.

Skid fin.—A longitudinal vertical surface, usually placed above the upper wing to increase the lateral stability.

Skin friction.—The tangential component of the fluid force at a point on a surface.

Slat.—A movable auxiliary airfoil, attached to the leading edge of a wing, which when closed falls within the original contour of the main wing and which when opened forms a slot.

Slip.—The difference between the geometrical pitch and the effective pitch of a propeller. Slip may be expressed as a percentage of the mean geometrical pitch, or as a linear dimension.

Slipstream.—The current of air driven astern by the propeller.

Slot.—The nozzle-shaped passage through a wing whose primary object is to improve the flow conditions at high angles of attack. It is usually near the leading edge and formed by a main and an auxiliary airfoil or slat (*see also* Slat).

Span.—The maximum distance, measured parallel to the lateral axis, from tip to tip of an airfoil, of an airplane wing inclusive of ailerons, or of a stabilizer inclusive of elevator.

Speed, cruising.—The cruising speed is the highest constant velocity at which the airplane can accomplish a specified range carrying at least the design useful load.

Speed, high.—The high speed is the maximum velocity obtainable in level flight at design altitude of the airplane and at the normal rated engine power at that altitude.

Speed, maximum.—The maximum velocity obtainable in steady level flight regardless of altitude.

Speed, operating.—The operating speed is the velocity obtained in level flight at design altitude of the airplane at not more that 75 percent of normal rated engine power.

Spin.—A maneuver in which an airplane descends along a helical path of large pitch and small radius while flying at a mean angle of attack greater than the angle of attack at maximum lift (*see also* Spiral).

Spin, flat.—A spin in which the longitudinal axis is less than 45° from the horizontal.

Spin, inverted.—A maneuver having the characteristics of a normal spin except that the airplane is in an inverted attitude.

Spin, normal.—A spin which is continued by reason of the voluntary position of the control surfaces, recovery from which can be effected within two turns by neutralizing or reversing all the controls. Sometimes called "controlled spin".

Spin, uncontrolled.—A spin in which the controls are of little or no use in effecting a recovery.

Spiral.—A maneuver in which an airplane descends in a helix of small pitch and large radius, the angle of attack being within the normal range of flight angles (*see also* Spin).

Stability.—That property of a body which causes it, when its equilibrium is disturbed, to develop forces or moments tending to restore the original condition.

Stability, automatic.—Stability dependent upon movable control surfaces automatically operated by mechanical means.

Stability, directional.—Stability with reference to disturbances about the normal axis of an aircraft, that is, disturbances which tend to cause yawing.

Stability, dynamic.—That property of an aircraft which causes it, when its state of steady flight is disturbed, to damp the oscillations set up by the restoring forces and moments and gradually return to its original state.

Stability, inherent.—Stability of an aircraft due solely to the disposition and arrangement of its fixed parts; that is, that property which causes it, when disturbed, to return to its normal attitude of flight without the use of the controls or the interposition of any mechanical device.

Stability, lateral.—Stability with reference to disturbances about the longitudinal axis; that is, disturbances involving rolling or sideslipping. The term lateral stability is sometimes used to include

both directional and lateral stability, since these cannot be entirely separated in flight.

Stability, longitudinal.—Stability with reference to disturbances in the plane of symmetry, that is, disturbances involving pitching and variation of the longitudinal and normal velocities.

Stability, static.—That property of an aircraft which causes it, when its state of steady flight is disturbed, to develop forces and moments tending to restore its original condition.

Stabilizer (airplane).—Any airfoil whose primary function is to increase the stability of an aircraft. It usually refers to the fixed horizontal tail surface of an airplane, as distinguished from the fixed vertical surface.

Stabilizer setting.—The acute angle of the reference chord of the horizontal stabilizer to the longitudinal reference axis of the airplane measured in the plane of symmetry. Stabilizer setting is considered positive when the leading edge is up.

Stagger.—The distance between specified points on two adjacent wings measured parallel to the longitudinal reference axis usually between the ⅓ chord points of the mean aerodynamic chords of the individual wings or between the leading edges of the root reference chords. The stagger is positive when the upper wing is in advance of the lower.

Stall.—The condition of an airfoil or airplane in which it is operating at an angle of attack greater than the angle of attack of maximum lift.

Static pressure.—The force per unit area exerted by a fluid on a surface at rest relative to the fluid.

Static tube.—A cylindrical tube with a closed end and a number of small openings normal to the axis, pointed upstream, used to measure static pressure.

Step.—A break in the form of the bottom of a float or hull, designed to diminish resistance, to lessen the suction effects, and to improve control over longitudinal attitude.

Streamline.—The path of a particle of a fluid, supposedly continuous, commonly taken relative to a solid body past which the fluid is moving; generally used only of such flows as are not eddying.

Streamline form.—The form of a body so shaped that the flow about it tends to be a streamline flow.

Strut.—A compression member of a truss frame.

Supercharger.—A pump for supplying the engine with a greater weight of air or mixture than would normally be inducted at the prevailing atmospheric pressure.

Sweepback.—The acute angle between a line perpendicular to the plane of symmetry and the plan projection of a reference line in the wing.

Tab.—An auxiliary airfoil attached to a control surface for the purpose of reducing the control force or trimming the aircraft.

Tail-heavy.—The condition of an airplane in which the tail tends to sink when the longitudinal control is released in any given attitude of normal flight (*see also* nose-heavy).

Tail surface.—A stabilizing or control surface in the tail of an aircraft.

Take-off.—The act of beginning flight in which an airplane is accelerated from a state of rest to that of normal flight. In a more restricted sense, the final breaking of contact with the land or water.

Taper in plan only.—A gradual change (usually a decrease) in the chord length along the wing span from the root to the tip, with the wing sections remaining geometrically similar.

Taper in thickness ratio only.—A gradual change in the thickness ratio along the wing span with the chord remaining constant.

Taper, double (wings).—A wing is double tapered when both the chord and the thickness ratio vary along the span.

Trailing edge.—The rearmost edge of an airfoil or of a propeller blade.

Velocity, terminal.—The hypothetical maximum speed that an airplane could attain along a specified straight flight path under given conditions of weight and propeller operation, if diving an unlimited distance in air of specified uniform density. If the term is not qualified, a vertical path angle, normal gross weight, zero thrust, and standard sea level air density are assumed.

Venturi tube (or venturi.)—A short tube of varying cross section. The flow through the venturi causes a pressure drop in the smallest section, the amount of the drop being a function of the velocity of flow.

Wash.—The disturbance in the air produced by the passage of an airfoil. Also called the "wake" in the general case for any solid body.

Wash-in.—A warp of an airplane wing giving an increase of the angle of attack toward the tip.

Wash-out.—A warp of an airplane wing giving a decrease of the angle of attack toward the tip.

Wind, relative.—The velocity of the air with reference to a body in it. It is usually determined from measurements made at such a

distance from the body that the disturbing effect of the body upon the air is negligible.

Wing.—A general term applied to the airfoil, or one of the airfoils, designed to develop a major part of the lift of a heavier-than-air craft.

Wing-heavy, right or left.—The condition of an airplane whose right or left wing tends to sink when the lateral control is released in any given attitude or normal flight.

Wing profile.—The outline of a wing section.

Yaw.—An angular displacement about an axis parallel to the normal axis of an aircraft.

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